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ABSTRACT

Presented are 36 articles originally published in "Science" during 1973-75. The articles are divided into six sections entitled: (1) Policy Considerations; (2) Energy, Environment and Conservation; (3) Perspectives on Needs and Supplies of Resources; (4) Finding the Processing Minerals; (5) High Technology Materials; and (6) Wood and Plant Materials. Some of the topics discussed are: (1) international trade in raw materials; (2) basic research in materials; (3) energy implications of materials processing; (4) limits to exploitation of nonrenewable resources; (5) chemicals from coal; (6) seawater and the geochemistry of ore formation; (7) brittle ceramic materials for high temperature structures; and (8) the national forests. (BB)

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Edited by
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Introduction

The New World of Materials

Philip H. Abelson and Allen L. Hammond

After a short but severe recession, economic growth is beginning again in the United States and, more slowly, in other countries. But the economy will not be restored to the precise conditions existing in 1973. The reasons can be found in a new set of realities affecting energy and raw materials. That supplies of these basic commodities will remain adequate in the future can no longer be taken for granted. Indeed, the prospects for economic prosperity and perhaps for peace in coming decades will depend on how the world adjusts to new constraints and new expectations regarding these key ingredients of human endeavor.

What is new in regard to energy and materials is wide recognition that exponential growth cannot go on forever—a fact that has been brought home to many peoples of the world with especial force with respect to energy. It is not just a quadrupling of the price for oil in international trade but also the prospect of eventual physical limitations to its supply that is forcing this reconsideration. One by one the oil producers of the world will repeat the experience of the United States, where production reached a peak in 1970 and has since declined. Economies based on oil face the necessity of changing to other energy sources, a change that will have effects on the industrial and social character of the countries involved comparable in magnitude to the effects of the shift from wood to coal or from coal to oil and natural gas.

Profound changes are also occurring in conditions affecting the supply of raw materials. Among the new factors is a trend toward nationalization of foreign-owned mining properties or other measures to give effective control over natural resources to the host country. High energy prices are making prohibitively expensive the recovery of some low-grade ores and forcing reconsideration of energy-intensive processing methods, especially in the primary metals. New concern about the environmental impact of mining, lumbering, and materials processing and increasing restriction of access to resources on public lands are also constraining materials production in a major way. Taken together with financial markets that make raising capital difficult, these developments have created conditions dramatically different from those of a decade ago—a new world of materials. Indeed, what is perhaps most remarkable is that their cumulative impact has not yet disrupted the supply of materials in a major way.

Growing Nationalization

The lesson of the oil cartel's success in raising petroleum prices has not been lost on either the countries that export materials or those that import them. Thus far, efforts to extract higher prices for bauxite or other materials have not been too sucessful. But nationalization of copper, bauxite, tin, and, most recently, iron mines has been accelerating, with more than 12 Third World countries taking such actions during 1974 and 1975. Last year, for example, Venezuela nationalized several mining properties that supplied 15 million tons of iron ore annually, an amount equal to 30 percent of the iron ore imported by the United States. The expropriation of mines by these developing countries and the declared intent to ultimately control their own natural resources by many more have drastically altered the international materials climate and introduced a new and largely negative element into the calculus of investment in resource development. Attention to where supplies of raw materials come from and their vulnerability to sudden interruptions has become very keen among industrial executives and has stimulated new consideration of alternative sources of supply.

For the United States as a whole, imports constitute more than half of the supply of aluminum ore, tin, chromium, asbestos, and nearly two dozen other important materials. For a few key metals, the effects of a sudden cutoff could be very disruptive indeed. Stainless steels, for example, depend on chrome. Obviously, prudence dictates that stockpiles of the most vulnerable materials be maintained. Given sufficient time, however, new sources of supply can be developed or alternative materials that serve the same function can be brought into use. The demonstrated existence of the necessary technologies can, in fact, serve as a deterrent to cutoffs or a restraint against drastic price increases. There is yet time to develop the requisite technologies for a number of vulnerable materials before such situations arise, rather than playing catch-up as in the case of energy technologies alternative to oil.

Energy use is a pervasive consideration throughout the materials cycle, from mining or harvesting, to processing, to disposal or recycling. Nearly 16 percent of U.S. energy consumption is now devoted to materials production. Wood product industries are somewhat of an exception among materials producers in that they can supply a substantial portion of their energy needs by burning wood chips and other waste, and are thus buffered to some extent from the effects of higher energy prices. Other materials producers are not so fortunate.

For most minerals, the largest portion of energy use occurs in concentrating the raw ore prior to smelting or other processing. Low-grade ores require the crushing and grinding of much higher volumes of material and are thus more consumptive of energy. Given enough low-cost energy, of course, there is no limit to the grade of ore that can be exploited. But in practice, high energy prices are an increasingly severe constraint that has focused new attention on less energy-intensive means of extracting and processing ores and has raised new questions about ultimate limitations to materials supplies. It now seems unlikely, for example, that copper ores containing less than about 0.1 percent copper will be mined at all (the ores currently mined average about 0.7 percent copper). The trend to lower-grade ores as richer deposits are

exhausted will intensify the energy squeeze on the materials pipeline.

Declining grades of ore also place materials needs on a collision course with environmental aspirations, since they imply larger volumes of mine spoil. A more fundamental constraint is increasing awareness of the health hazards associated with leakages from the materials cycle of such substances as asbestos, halogenated organic compounds, and heavy metals. The costs of cleaning up water effluents from mines and materials processing plants to meet the standards mandated by existing laws is estimated at about $20 billion over the next 8 years, which gives a measure of the effort required. Higher prices for materials and continuing, perhaps growing tension between environmental values and the availability of materials appear likely.

With such constraints, the long-term prospect for expanded supplies of raw materials is mixed at best. Barriers to development and exploitation of materials resources are to some extent balanced by improving techniques for finding and winning minerals from the earth's crust. Knowledge of how ores are formed is being advanced by the concept of plate tectonics, and the Earth Resources Technology Satellite is proving most useful in discovering ore deposits. Application of modern biological science and management techniques seems to promise improved yields and more abundant supplies of renewable materials such as wood. It is even possible that the demand for materials, at least in the United States, could grow much more slowly in the future. A recent Harris poll showed that 90 percent of those polled – a figure so high as to constitute a mandate – agreed that "we here in this country will have to find ways to cut back on the amount of things we consume and waste." Nonetheless, even maintaining the present materials base will be increasingly difficult in coming decades.

Among the most rapidly growing constituents of the materials base are wood products, plastics, and other synthetics. The economy is especially dependent on products derived from natural gas and petroleum. The annual tonnage of such synthetics is somewhat less than that of steel, but in volume they surpass it. Most of the basic feedstocks for these materials could be derived from coal, wood, or plants. Indeed, at one time the nation's supplies of ethyl alcohol, acetone, and butanol were produced by fermentation of grain or molasses. These three chemicals are or could be used as a substantial fraction of the inputs for plastics and other synthetics. A convenient starting material might be glucose obtained from the starch of grains or the cellulose of trees by hydrolysis. These examples serve to illustrate the point that there appear to be many new opportunities to exploit the feedstock potential of renewable resources and of coal, opportunities created by the high price and, ultimately, the scarcity of hydrocarbons from oil and natural gas.

Similar considerations point to another long-range opportunity or even necessity, that of finding a broader range of uses for the abundant minerals of the earth's crust. These minerals and the materials such as glass and cement that can be made from them are derivable from common rocks, a source of supply that is not vulnerable to foreign control. Research into what can be done with such materials would benefit the rest of the world as well.

The materials research effort in this country has shown an impressive ability to explore basic physical and chemical properties and to create new materials or old materials with new properties with that knowledge. These discoveries have often set the pace for the development of new and more sophisticated technologies. Of equal importance, however, are questions of raw materials supply and of industrial processing under energy and environmental constraints. These areas have received less emphasis, especially in academic institutions, but are central to the functioning of the economy. They deserve more attention in the future.

Looking to the Future

This special issue was inspired by the new conditions surrounding materials supply and seeks to examine in more detail many of the themes and problems mentioned above. More extensive treatments of materials supply can be found elsewhere (a selected list appears in the bibliography). For the most part, the articles of this issue are future-oriented. Usually when attempts are made to look ahead, the seers tend to predict disaster or utopia. The consensus of the authors in this volume is that there are problems but, at least in principle, they are solvable. A representative sample of the tone of the content is provided by Landsberg in his overview of recent trends and issues. He points out that the United States has not been experiencing exponential growth in the use of materials. During the past two decades per capita consumption has been about level. Landsberg minimizes the disaster scenario presented in the Club of Rome's 1972 report. He is skeptical of the view that he imputes to the Club of Rome "that materials exhaustion looms as one of the horsemen of their special breed of Apocalypse and could bring civilization tumbling down." He cites contrary arguments and viewpoints.

Nevertheless, Landsberg is not complacent. He points to a new societal hostility to the discovery and production of materials. The arena of action ranges from removal of land from exploration to stringent regulations affecting extraction or harvesting, treatment, and transformation. An important development is withdrawal of federally owned land from mining activities. Prior to 1968, only 17 percent of these lands were forbidden to mining. By 1975 the total had risen to 67 percent, with the prospect that all might be forbidden by 1980. These lands comprise about one-third the area of the United States and contain much of the best potential mineral resources.

In his article on international trade, Fried discusses the great commodity price boom of 1971-74. During that period prices rose by 159 percent. In 1972-73 they jumped 67 percent. These increases were the largest in the past 115 years.

The boom in commodity prices began before the sharp rise in oil prices. It was in part conditioned by imbalances in supply and demand, which led to fears of an era of permanent shortages. Once the inflation began it fostered instability of currencies and speculative fever. As an example, Fried points to the role of the Japanese in amplifying price fluctuations and cites figures for their imports and exports. For example, their annual imports of copper have been averaging about 270,000 tons and exports about 30,000 tons. In 1973 imports rose sharply to 395,000 tons. This was followed in 1974 by exports of 280,000 tons. In 1973 the price of copper hit a high of about $1.50 a pound. In 1974 the price dropped to as low as $0.52.

In his analysis Fried emphasizes the cyclical nature of the commodity boom. He urges that the present period of relief from hysteria be used to take measures to avoid future shocks of boom or bust. One step would be to create buffer stocks that could be increased during periods of low price and made available when prices rose.

The cost of various forms of energy will be a crucial determinant of the kinds of materials that are available and are used in the future. If energy were to be abundant and sufficiently cheap, very low-grade deposits could be utilized. However, in the future some forms of energy, notably hydrocarbons, will not be cheap and abundant. Dependence on foreign sources of oil will grow rapidly during the next 5 years, rendering the whole economy, including materials aspects, vulnerable to sharply advancing costs and even stoppages of supplies.

Fig. 1. Copper ores as low as 0.4 percent copper are recovered from Kennecott's Bingham mine near Salt Lake City, Utah. However the low grades are economical in part because some precious metals are also recovered. (Photo courtesy of James Boyd, Materials Associates, Washington, D.C.)

Accordingly, an examination of the usage of energy in the winning and processing of materials is relevant. In addition to being aware of costs and availability of materials, we need to know their energy costs. In this issue Hayes provides substantial information concerning the energy consumption involved in the production of materials of major importance.

Two articles, one by Cook and the second by Goeller and Weinberg, explore the limits of exploitation of nonrenewable minerals resources; energy is an important consideration in their comments. The first article provides some historical background as a basis for extrapolating into the intermediate future. The second article looks at the more distant future.

For many years economic geologists have warned of coming exhaustion of important minerals, and indeed the rich deposits of many ores have been exhausted. However, development of new methods and efficient earth-moving equipment and abundance of low-cost energy has permitted exploitation of lower-grade ores. At one time the cutoff grade for copper ore was 3 percent. Now in some places a content of 0.35 percent is exploitable (Fig. 1).

However, Cook cites information on copper ore bodies which leads him to believe that in the long term it will become extremely difficult if not impracticable to obtain large supplies of copper. He points out that the volume of recoverable copper does not increase very greatly as the ore grade drops lower than present levels. He also mentions the exhaustion of mercury ore deposits in the United States. It seems plausible that supplies of some elements will one day be effectively exhausted.

Goeller and Weinberg are very optimistic about future supplies of materials, provided adequate energy is available. They recognize that reserves of some individual elements may become largely exhausted. However, they point to the relative ease of substitution. For example, copper as an electrical conductor can be replaced by aluminum. They cite a study of the use of mercury which demonstrates that virtually all of the functions served by that element can be filled in other ways. Moreover, the major tonnages of inorganic materials that are presently used are derived from abundant elements, particularly iron and aluminum. Looking a distance into the future, they foresee only a limited number of possible problems of scarcity—phosphorus, and energy in the form of CH_4. From this discussion and from other items in this issue, one draws the impression that given time and supplies of energy, technology and science can provide the necessary flexibility to gradually overcome scarcities of particular materials. At the same time, it should be obvious that often as long as a decade or more must elapse before the system can adjust fully.

If our industry were to be suddenly denied supplies of an element vital to high technology, dislocations could occur that would last for some time. Even mild shortages could lead to sharply higher prices for specific items. At present there are some 23 minerals for which the United States must import most of its needs. A Bureau of Mines program described by Kirby is aimed at reducing potential vulnerability by testing methods of winning supplies from indigenous materials. It also serves as a form of technological insurance against excessive price demands from foreign suppliers. An example is work designed to produce alumina from domestic sources such as clay or anorthosite. At present almost all supplies of alumina are imported. The program will examine a number of different methods in pilot plants. Should a crash program later become necessary to provide domestic sources of alumina, years would be saved in arriving at full-scale production.

Chemicals produced annually from oil and gas have a value in excess of $30 billion. The products are important to many

aspects of the economy, including agriculture, clothing, home furnishings, and transportation. Feedstocks to produce the large variety of products take about 10 percent of the oil and gas supply.

At one time many of the feedstock chemicals were obtained from coal, primarily as a by-product of coke ovens. However, from about 1950 on, the principal source was petroleum. Oil and natural gas had advantages of price; they also were clean. Moreover, the oil industry processes huge volumes of fluid and is adept at plucking out individual chemical species. So large is the volume of processed oil that even a minor constituent is available in substantial tonnages.

However, petroleum reserves of the United States are declining. We face a future in which availability of petroleum feedstocks is uncertain and in which they may be very costly. Because of the long time span required to convert small-scale studies to large production plants, it is appropriate to examine alternative sources of organic chemical feedstocks. Coal is one of the major potential sources. In this issue, Squires surveys the current state of the art of obtaining chemicals from coal and identifies new and promising findings that represent substantial advances over the older coal tar techniques. Among other topics he discusses gasification with steam and oxygen, partial gasification with steam, flash pyrolysis, and flash hydrogenation. The latter two processes seem particularly promising.

Chynoweth provides insights on the interaction of materials and high technology. High technology is a major user of many of the rarer elements, but at the same time advances in technology have led to great savings in the use of energy and materials in performing a given function. Chynoweth cites the simple example of the modern solid-state calculator, which has replaced the earlier heavy mechanical version. Small silicon chips with their complex circuitry fill the functions of great numbers of vacuum tubes, resistors, and condensers. They do this reliably and with little energy cost. Chynoweth points out that the replacement of mechanical calculators by solid-state devices is a higher order of substitution than, for example, aluminum for copper, and he refers to it as a functional substitution. Other examples cited are the use of adhesives instead of nuts and bolts for joining and of jet engines instead of piston engines and propellers in aircraft.

Chynoweth cites further examples of contributions of solid-state electronics to conservation of materials through miniaturization and through substitution of functions. The power of the ingenuity of the electronics industry is such that it is capable of vast changes and adjustments and of responding to evolving constraints in the costs of energy and materials. The picture implied in Chynoweth's vision is a society whose standard of living increases while use of energy and materials declines.

The Potential of Wood

At one time wood was the principal energy source for the United States. But after 1860 it was gradually supplanted by coal, and it came to be used mainly for building materials and paper products. As long as vast areas of virgin timber were available, there was little effort to improve silviculture.

With large amounts of cheap oil and natural gas available as feedstocks, there was little incentive to explore the chemical or energy potential of trees. Recently, with the general realization that petroleum resources are finite, diminishing, and likely to become more costly, increasing attention has been focused on wood. The potential of trees as renewable resources of materials, chemicals, and energy is substantial. About a third of the land area of the world and of the United States is forested. The biological potential of wooded areas is such that with a vigorous effort the United States could, in principle, maintain an austere but satisfactory economy based on trees as a principle energy source. Recent experiments have shown that wood can be converted by hydrogenation into liquid fuels. Wood has the advantage of being relatively ash- and sulfur-free. The growing stock of the world's forests totals about 300,000 million cubic meters of wood with an annual increment of about 3,000 million cubic meters, which might be substantially increased by better management.

Thus wood has large potential as a long-term renewable resource applicable to needs for energy and materials. Recognizing the important role of wood for the future, a National Academy of Sciences committee headed by J. S. Bethel has been conducting a study on renewable resources for industrial materials. Three articles related to that study appear in this issue. Emphasis is on the use of wood principally as a source of building materials and of paper and related products. The total quantities involved are impressive. Jahn and Preston point out that annually 250 million tons of raw wood is processed—an amount about equal to the production of all metals, cements, and plastics. An important use is in structural materials, and here wood has an important energy advantage. For example, steel floor joists require 50 times as much energy as their wood counterparts. Aluminum framing for exterior walls is about 20 times as energy-intensive as wood framing.

Spurr and Vaux provide an analysis of the biological potential of U.S. forests. They state that potential growth is much greater than current growth. Much of the western forest land is still covered with old-growth forests, for which net growth is negligible because the rate of mortality approximates the rate of growth in the surviving trees. They cite a number of ways in which yields could be improved, including introduction through planting of genetically faster-growing trees.

In the three articles related to the Academy study there are repeated references to institutional impediments to effective management of our wooded lands. One factor cited is the federal government. This unwieldy giant comes in for special treatment in an article by Clawson. He takes an economist's approach to federal management of its forests. He estimates that the timber on the public lands has a value of $42 billion and points out that the government obtains only about a 1 percent annual return on this huge sum. In comparison to private enterprise, this performance is very poor. Moreover, in the forests managed by industry, net growth per acre is almost double that on federal lands.

Renewable resources are crucial to an enduring human civilization. The articles herein dealing with this topic leave the impression that this nation has not yet got its priorities straight. Indeed, materials of all kinds are so basic to the continuance of our society that the country would be well served by increased attention and more to the point—some constructive action to insure a continued supply.

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Policy Considerations

Materials: Some Recent Trends and Issues

Hans H. Landsberg

Man has always been preoccupied over tomorrow's supplies. While immediate needs are perhaps less in question now, the dynamics of growth have enormously broadened the scope of concern. One useful definition of "growth" is a multiplication of options—of opportunities, that is, to do conventional things in more than one way, and to add to them ways of doing new things. Once provisions of minimum food and shelter needs have been assured, growth has meant added ways of occupying one's time and most of these involve the use of *materials*. (For this discussion, materials comprise basically the nonenergy minerals, forest products, fibers, both natural and man-made, and those chemicals not already covered in the above categories. Excluded are food, energy sources, and drugs.) What we wear, move on and in, live, sit, and lie in, use to fashion tools, simple and complex, or need for modern entertainment, recreation, education, and much of the healing arts, all this incorporates materials as here defined.

The volume and variety of materials used in modern society have grown steadily. When the President's Materials Policy Commission—more commonly remembered as the Paley Commission—published its findings in 1952 (*1*), it reported that annual per capita consumption in the United States of all materials, food and energy included, amounted to 18 tons per citizen. Census data in constant dollars suggest that, in the two decades that have since elapsed, the 1952 figure may have risen by some 10 percent (*2*). Within that all-inclusive category, materials as defined here have lost in relative importance, with per capita consumption about level. Although data are fragmentary, they indicate that in the developing countries per capita use of materials has been growing, starting of course from a much lower base. A good illustration is a better than doubling in per capita steel consumption in India between 1950 and 1970.

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Depletion, Adequacy, and All That

The rise in aggregate consumption has given birth to two ideas. One is the opinion that materials exhaustion could bring civilization tumbling down (*3*). The other is a rather widespread opinion that the advanced societies are moving away "from goods to services" and will continue to do so. A gradual reduction in the rate of growth of materials consumption and eventually perhaps in consumption itself would follow. There is yet a third group of theorists who point to mankind's past success in overcoming the threat of scarcity as grounds for believing that we are neither threatened by exhaustion nor must we seek salvation in a transition to a service-oriented economy. Specifically, reliance is put on more efficient ways of gaining materials in conventional environments, of identifying new environments and new materials, and proceeding to more efficient use and reuse of materials.

The battle among these groups has swayed rather indecisively. The impact made by the *Limits to Growth* school (*3*) has been massive, especially in some European countries that have traditionally been materials-poor.

Stripped of the moral and emotional overtones that often accompany the main theme, there remains a core of insight to the warnings; this core deserves serious consideration when appropriately formulated. Brooks and Andrews (*4*) point to the declining usefulness of distinguishing between renewable and nonrenewable (finite) resources and suggest that, given the dimensions of the globe, even finite resources are in reality not a stock but a flow resource. They caution, however, that the rub comes in managing the extraction and processing stages because the effects of earth-moving and other disturbances of the environment present increasingly difficult and costly obstacles that can overwhelm the task of supplying rising quantities of desired materials and may constitute the real limits to growth.

Companion arguments focus on the relative magnitude of the earth's unexplored and explored portions, the ocean bed as a future technologically feasible supply base for at least half a dozen metals, and the known very large occurrences of a few minerals—such as iron, aluminum-containing ores, silicates, carbon, titanium, and magnesium—on which could be based, if not an exact replica of today's society, a reasonable variant thereof. While as yet little explored, the building of credible scenarios incorporating severe constraints with regard to the availability and variety of materials could usefully illuminate this particular issue, sometimes dubbed "the worst case" approach. The point is not to stress the fact that mankind once existed with a small fraction of our materials supply, so why couldn't we; but rather it is to inquire, knowing what we know now, to what extent, in what direction, and at what cost a greatly restricted materials menu would force us to modify our way of life.

A recent entry, represented also in this issue (*5*), is the idea that, given sufficient low-cost energy, the materials problem tends to disappear as energy becomes a substitute. Consequently, the emphasis shifts to the limits set for energy consumption by way of heat release or other accompanying circumstances of energy production and consumption, that counsel at least prudence.

By and large, the adequacy debate seems at a standoff. The *Limits to Growth* approach no doubt has increased our sensitivity to the depletion issue. At the same time, the bigger-than-life dimensions of the model have limited its usefulness to policymakers and maximized the number of objections based on its mechanistic framework (*6*) and its neglect of important variables that could be assumed to be operating in the early portion of the time span of the *"Limits"* model. In contrast, no technological breakthroughs of the kind that would give the argument that depletion continues to be shifted forward in time a winning edge have occurred; nor has there been a breakthrough, for example, in seabed material recovery, or a switch to new abundant mineral resources in, say, the aluminum area, or in recovery methods, such as leaching as opposed to excavation.

No wonder that proposals to engage in a systematic, thorough drilling exercise have found some enthusiastic supporters, especially among geologists. The idea of "inventorying" as a means of arbitrating the controversy has perennial appeal, especially when accompanied by estimates that attempt to show this to be a relatively low-cost venture.

New Hostility

A relatively new issue in materials affairs is that increasing demand for materials has been paralleled by increasing obstacles to their discovery and production. Thus, even if we could, at a tolerable cost, be better informed of the location and characteristics of hidden treasures, it is no longer legitimate to assume that (i) exploration would be generally welcomed and (ii) exploitation would follow. Ironically, now that we have better tools than ever to locate deposits, or—to broaden the analysis to encompass nonminerals—to increase the harvest of reproducible materials supplied by trees and other living organisms, not only has a large and growing segment of society developed an intense hostility toward such activities, but the institutional setup has been modified to give their voices both platforms and operating room. The arena of action ranges from removal of land from exploration to stringent conditions affecting the process of extraction or harvesting, treatment, and transformation.

Federally owned land has come under a growing number of statutes that bar it from mining activities. Examples of these exclusions are wildlife refuges, national parks, reclamation lands, native lands, and other exclusions under the Alaska Native Claims Settlement Act of 1971. The list does not—nor can it—include citizen opposition to individual undertakings in specific locations.

Jack Carlson, Assistant Secretary for Energy and Minerals, U.S. Department of the Interior, in addressing the American Mining Congress on 28 September 1975, put some figures on these trends:

> In all of our history up until 1968, the Federal Government had effectively withdrawn from mining and exploration about 17% of all Federal lands. This comparatively small amount was something we could all live with.
>
> But suddenly, in 1968, it seemed as though the dam had burst as withdrawal after withdrawal piled up. Without coordination, without knowledge of what was being done elsewhere in the Government, and certainly with no desire to cripple domestic mineral capability, the Congress and Federal agencies totally withdrew or significantly restricted vast acreages of land. Today, some 500 million acres, the size of every State east of the Mississippi except Maine—67 percent of all Federal lands—are off limits to miners.
>
> And, there has been no let up. More withdrawals were identified last year than the previous year. The momentum is growing, and we can expect the percentage of withdrawals to increase. If the rate established in 1974 were to continue, we could close all public lands, one-third of the land area in the U.S., and some of our best mineralized areas—by 1980.

The emergence of this hostility and its reflection in recent laws are not, of course, fortuitous. At the rate of exploitation engendered by levels of population and income and their rates of growth over the past three decades, the scars inflicted on the environment, animate and inanimate, are correspondingly large and conspicuous. To this has been added a change in the way in which ore exploration and mining as well as foresting activities are regarded. Once looked upon as free-wheeling ways of life that offered escape from constraints imposed on citizens living in settled urban and rural areas, they have now taken on the image of near-illegitimate intrusions by man upon nature, violating pristine surroundings, promoting boom-and-bust communities, and burdening local authorities with an unwanted influx of new migrants—in other words as highly undesirable events. If that is the way to wrest materials from their habitat, let it occur elsewhere, seems to be the spreading attitude. Applied to a whole country or continent, "not here" quickly escalates from a local to a national issue. Thus there seems to be a change from wondering whether the stuff exists to wondering whether it can be produced, with only little consideration being given to what Freeman Dyson has called "The Hidden Cost of Saying No" (*7*).

Goods versus Services

Perhaps there is a way out if we are indeed slated to develop into a society in which production of goods is rapidly giving way to production of services. With demand diminishing, first in its rate of growth, then absolutely, the opportunities for clashes of competing objectives would equally diminish. It is, therefore, useful to review the nature of this phenomenon, sometimes referred to as the "post-industrial society." As I have suggested elsewhere (*8*), the concept is somewhat at variance with the facts. To begin with, the so-called service industries are in part quite material-intensive: transportation and utilities are good examples. Consumer expenditures for services in the National Accounts (*9*), as opposed to service industries—a murky category—equally involve heavy materials use, extending to such apparent nonmaterial categories as recreation, medical services, entertainment, and others as practiced in our society. Consider, for example, that listening to an opera in the Kennedy Center in Washington is associated with three floors of garage space filled with automobiles that, on the average, may travel 10 to 15 miles (1 mile = 1.6 kilometers) each way! To illustrate more formally, when a couple of years ago I sorted out the appropriate categories in the 1970 National Accounts, I found that, of an estimated $39 billion of consumer expenditures for recreation, fully 17 consisted of durables and 11 of nondurables, while only the remaining 11, or less than one-third of the total, were classified as "services" proper; even portions of this last category may in turn contain a quota of materials.

Nor, contrary to impressions sometimes gleaned in the media, have we gone very far in the "turn to services." Only when shifts in employment are considered do we find a pronounced and significant trend to services: from 56 to 68 percent of total employment in the two decades ending in 1970 (a large part of this change reflecting the decline in agricultural and the growth in government employment, especially education). In contrast, services grew only from 34 to 38 percent of total consumer expenditures during the same 20 years, and the share of the so-called service industries, their fuzzy definition apart, was from 60 to 63 percent of the gross national product (GNP), corrected for inflation.

If the record of the past two decades renders it questionable to count on a reduction in the rates of the use of materials because the service sector will grow at the expense of the goods sector, this is not to say that such rates need to continue at their historic trend. There are other ways in which materials use may be reduced. Some, like Malenbaum (*10*) and Brooks (*4*) have attempted—mostly for metals—to systematize this reduction by postulating materials-intensity factors that decline with rising per capita GNP. The idea is seductive, even though the statistics adduced lack a description of underlying process and motivations. Students of U.S. energy history are reminded of a parallel in which, over a period of some 100 years, the ratio of per capita energy use to per capita GNP first increased, then flattened out, and then declined. Various explanations have been offered to account for the underlying real events (*11*). In the case of materials, this phase of research remains to be tackled.

Moreover, in the absence of a common measure of materials use—other than a monetary unit—the thesis so far rests on historical trends and projections for single commodities. Substitution effects thus cannot be isolated. Over extended periods in which materials of petrochemical origin, for example, have risen with extreme rapidity, one would like to test the hypothesis for materials in the aggregate. Such an effort in combination with reasoned and specific explanations would assess, for example, whether a country passing through a heavy capital goods investment phase, including construction of major transportation networks, public facilities, and the like, is especially materials-intensive;

how far improved efficiency in use plays a role, as economies mature; whether, as suggested above, the trend is toward newer materials, imparting to the old standbys—such as iron, copper, lead, and zinc—a downward momentum, which may be misread as a general "law," and the like. In the meantime, it is probably prudent not to look to the possible existence of such long-term relationships—an intensity rise and decline law—as offering a way out of contemporary problems associated with materials production and use.

Materials Extenders

Recycling and substitution are the two magic terms that suggest more immediate escapes from scarcity and are on everybody's agenda of remedies. Despite the fact that neither is new, knowledge for judging the opportunities they offer is scant. Recycling has been given added momentum since the "materials cycle" concept has been popularized and suggests that it can be beneficial in the path from extraction or harvesting to eventual disposal. But at the same time, we have become aware of the obstacles to recycling or reuse, some of them institutional, some technological, and some economic, that is, cost-associated. Estimates of the potential contribution to the total materials supply by "mining" after-use streams or stacks of materials depend on assumptions regarding the estimated length of the useful life of the product, efficiency of gathering mechanisms, recovery efficiency, characteristics of the recovered material in relation to the specifics of demand, and no doubt public policies designed to affect the incentives for increasing efficiency all along the line.

As the result of an attempt a few years ago to judge what metals might raise the contribution made by scrap if there were an active recycling policy, it was estimated that little in the way of added material could be expected for iron and lead (that is, recycling mechanism and incentives appear to be working effectively already), somewhat more for copper, and a great deal more for zinc and aluminum (*12*). In the last instance, the relatively recent emergence of the material as a large tonnage item inevitably means that the volume should rise as stocks of obsolete products come increasingly into the market. Given the large energy component in primary aluminum and the relatively small one in the secondary product, the prospect of a rising recovery potential is cheering, but much depends on creating the slope that will enable the secondary material to slide into use rather than disposal.

All this is in the future, however. The available statistics reveal no upswing in recycling up to now, a circumstance that may be linked as much to the institutional impediments as to the fact that the country has been in a recession and the prices of most primary materials have plunged from their heights of early 1974.

As for substitution, the upheaval in energy prices has upset the once widespread speculation that the more abundant minerals, like aluminum and magnesium, and those derived from oil and gas, would increasingly encroach upon their competitors. High energy costs of both are now an obstacle to expansion, and while their light weight gives them an advantage in some uses (for example, aluminum and plastics in motor vehicles), this must now be balanced against the demerit of a high energy input in their manufacture. Indeed, there has been occasional agitation for deliberately reversing the historical trend and substituting steel for aluminum, solely on the grounds that the former is less energy-intensive. Like most single-purpose policies, this one too suffers from the tunnel vision of its perpetrators. Very sophisticated and specific models would be required to decide which material has some over-all superiority in a societal sense; and since social goals no less than private ones are bound to change with changing circumstances, and especially technology, one would by such calculations, could they be satisfactorily made and implemented, saddle both the materials-producing and materials-using industries with great and continuing uncertainties. It is only one of many instances in which the overriding concern with energy-saving tends to push the burden onto the materials industries, a temptation that needs to be curbed. On a more general plane, it requires that we refrain from subordinating or even sacrificing aggregate cost estimates to calculations cast in physical terms.

A more recent suggestion designed to widen the materials horizon has been to consider substituting renewable—that is, biomaterials—for nonrenewable ones. Forest products, fibers, natural rubber, and others are said to merit a new look. The driving forces here are (i) the high price of energy in situations where the fossil fuels constitute the feedstock, supply the needed process heat, or both, (ii) the desire to ease the draft upon depletable minerals, and (iii) the thought that such a turn would be beneficial to some of the developing countries that have in the past lost their markets to synthetic substitutes.

The suggestion, or set of issues, cannot be evaluated in any generally valid sense. At some level of cost it may indeed be cheaper to derive feedstocks for the chemical industry from trees or other plants rather than from natural gas, oil, or coal; or natural rubber may regain part of the market it has lost in the past three decades to the synthetic product. If and when such conditions arrive as a consequence of relative shifts in costs and prices, judgments will have to be made whether these changes are desirable also from other vantage points. Land devoted to growing industrial materials, for example, would not be available for raising food crops. In order to increase productivity, fertilization would have to be greatly increased. Environmental problems are bound to emerge at various processing stages. They would require input of resources to manage them. While one ought to be alert to the opportunities offered by moving along this particular substitution route, comprehensive analysis is in order before facile hypotheses turn into conventional wisdom. It is perhaps worth stressing that forest land is likely to be eyed as potential cropland, as "energy farmland" to produce combustible timber, and as a source of chemical feedstock, quite apart from the traditional growing of timber for forest products. Multiple claims will have to be sorted out and reconciled.

The International Dimension

One cannot discuss recent trends and issues without at least a brief reference to the international scene. The setting of the problem is reasonably clear. The well-known issues in materials production—renewed concern over depletion, awareness of a materials "cycle" as opposed to separate material worlds, opportunities for and restraints upon recycling and substitution, speculation on long-term relationships between materials use and economic growth, the impact of energy and environmental costs—have most recently been joined by a wholly new issue: the demand for, and U.N. agreement on, a "new international economic order."

Materials, and not only those of mineral origin, tend to be subject to frequent and often violent fluctuations in demand, supply, and price. The costs of such fluctuations for the economies of both producer and consumer countries are probably substantial, although good research on that subject is only now beginning to be undertaken. It is certain in any event that the situation can be severely disruptive for countries that have one-crop or one-material economies. (As a consequence of the slump in copper prices, Zambia, living almost wholly off its copper resources, has been undergoing a severe economic crisis in 1975.) Employment, foreign exchange income, and government revenues are badly

depressed, and the social fabric of such an area may begin to tear under the stress. Consumer countries find the ups and downs unattractive, to say the least. The alternation of feast and famine causes a good deal of costly adjustment, sometimes transient, at other times permanent. Many, perhaps most, losses go unmeasured because they are diffused through the economy. Suppliers and consumers alike would probably gain if at least the most violent fluctuations could be avoided. Under the combined impact of the Organization of Petroleum Exporting Countries (OPEC) episode and newly aroused concerns over early depletion, the reasonable core of the matter has been transformed into a highly politicized claim by producers in the developing countries for a "fair price," which this time around is viewed as a means of restitution for past colonial exploitation, of escaping from the slings and arrows of price and demand fluctuations, and as a club with which to beat the rich countries and strengthen the domestic political base of exporter countries. Those who do not sell materials and cannot afford to buy them add their demand for an ill-defined "equal access" to materials, which, if it is to mean anything, must be understood to be a demand for an international redistribution of income, beginning with increased outside financial aid, to permit sharing the global materials pie.

The problem is not new; it used to be carried on under the "terms of trade" heading and played a large role in the creation of the U.N. Conference on Trade and Development (UNCTAD) in 1964. What is new is not only the highly charged rhetoric and the level of aspirations in terms of desired price ranges and other arrangements, but also a willingness of the rich consumer countries to listen and perhaps negotiate.

So great has been the OPEC shock that, no matter how fuzzy, the "new order" has in record time become an accepted concept, if not a fait accompli. Materials play a leading role in it. Rapidly, schemes that have long been anathema to the philosophy of the U.S. government, for example, have become legitimate items at least for discussion: buffer stock schemes, economic stockpiles, export compensation funds, and other tools that might defuse potential conflict or assure continuity of supplies (or both). In addition, novel ways of (i) channeling funds into mining ventures and (ii) taking the sting out of having resource exploitation ventures foreign-owned or managed (or both) are being discussed.

The points (i) and (ii) above seem especially constructive and urgent, for it is largely the economic recession that has given the world respite from the problems created by demand chasing inadequate supplies and driving up prices in the process. Yet the traditional lumpiness of investment and capacity additions in materials and especially in the extractive industries has undoubtedly been aggravated by political considerations; a reviving materials demand could easily trigger shortages and price boosts comparable to or perhaps worse than those that erupted in 1972–73.

Materials Diplomacy

It is much too soon to speculate what will come of the parleys that began in December 1975. They would be useful even if the "polylogue" among the more than two dozen countries, deemed to be representative of developed and developing countries, merely begins to reveal the priorities among the numerous aims of the participants.

The priorities of the industrialized, materials-consuming countries seem straightforward:

1) To invent mechanisms that will (i) minimize the possibility of supply interruptions, (ii) provide for higher and more stable incomes to Third World material exporters but prevent price revolutions à la OPEC, and (iii) create a political and legal climate that will encourage investment in exploration and development.

2) To quickly abandon generalities and come to cases, preferably product-by-product.

3) To provide for relief to the Fourth World or most seriously affected countries.

It is less easy to identify the real aims and perhaps even the potential gains of the developing countries. The principal reason is that the glamor of "materials power" is in all likelihood a mirage, although it may for a while yield significant gains (and what political leader will not try to reap them and heavily discount the longer future?). Higher raw materials prices, especially if they result from market restrictions, are not the high road to economic emancipation and growth. That rather lies through transfers and digestion of technology and capital, higher labor skills, education, and a more diversified economy.

It is quite probable that the OPEC example has set a misleading precedent. To be sure, larger revenues from higher-priced materials exports, if sustained, can fuel meaningful development schemes. But unless arrangements can be made on a comprehensive materials scale, that is, embracing competing materials, long-term price maintenance is likely to be difficult. Consumer countries, however, while perhaps ready to talk copper, or bauxite, or lead, are likely to balk at broad across-the-board negotiations and arrangements. Thus, the talks could aggravate rather than calm conflict, and as a result it may get harder rather than easier to mobilize support for sustained income and technology transfers—the real levers in development strategies.

Moreover, the tougher and more comprehensive the proposed new materials regime, the greater the consumers' incentive to evade its consequences. Consider indexation. On the not unrealistic assumption that at least a moderate degree of inflation is the way of life in the industrialized countries, the price of raw materials would rise continuously and automatically. What greater incentive to R & D to economize, recycle, and develop substitutes?

More Government

These considerations reveal yet one more clear trend in materials affairs: the steeply rising role of governments and their control over the marketplace. Government control has long been a fact in the planned economies. It is now a fact in many of the developing countries. And the recently expressed willingness of the outstanding holdout, the U.S. government, to play a larger role, makes one wonder if it will perhaps increasingly be a fact in the OECD (Organization for Economic Cooperation and Development) countries as a whole. This discussion suggests that the performance of the marketplace has not been all that wonderful, else there would not be such agitation to stabilize conditions. Yet, an enlarged government role heralds arbitrariness, unilateral decision-making, the instant conversion of technical disputes into matters of national concern and prestige, and attrition of attention to the economic dimension. Turning concern over materials supplies and prices into affairs of state may worsen the state of affairs.

State of the Economy

Masking the more fundamental issues that are likely to affect materials over the long run is the state of the economy, in this instance that of the world. The low level of activity from which the industrial nations find it hard to rise has severely depressed demand for most materials and led to heavy inventory buildup. As a result, the more forceful objectives of the materials exporters in the developing countries have been somewhat muted, while the consuming countries have had a breathing spell in which to review outlook and strategies.

U.S. imports of bauxite illustrate the sit-

uation: in the first nine months of 1975 they showed a decline of nearly 20 percent from the same period a year earlier. Within that aggregate there were severe dislocations: imports from Jamaica, Surinam, and Guyana declined by 23, 35, and 80 percent, respectively; those from Guinea increased by 50 percent. Not surprisingly under the circumstances, Jamaica retreated somewhat from its insistence that purchasers of bauxite must take minimum quantities—a provision adopted in 1974 to prevent dissatisfied customers from switching to competing suppliers. Amidst such fluidity it is difficult if not impossible to fashion policy and, if it exists, to live by it. Recession periods are not conducive to putting the squeeze on customers. All this could change quickly if and when the pace of demand picks up, and especially if it should do so rapidly and once again bump into capacity ceilings.

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International Trade in Raw Materials: Myths and Realities

Edward R. Fried

Only two years ago the industrial world was gripped by something close to hysteria over developments in international commodity markets. The phenomenon had complex roots which included the gloomy resource forecasts of Meadows *et al.* (*1*), fears that OPEC's success in controlling the oil market would touch off a proliferation of commodity cartels, and a spreading inflationary psychology. Against this background, the explosion of commodity prices then under way tended to be interpreted not in cyclical terms but as heralding a disquieting secular trend.

What made prevailing attitudes even more unusual was their political dimension. Concepts such as "commodity power" and "resource diplomacy" as well as predictions that the industrial countries would become engaged in a struggle over raw materials supplies became newly fashionable and received serious attention. Altogether the atmosphere produced a foreboding, if not a conviction, that power in the world had suddenly shifted from buyers to sellers of primary commodities.

Much of this apprehension lifted as the commodity cycle ran its traditional course. But enough lingers to warrant asking why the reactions to the events of 1972–74 were so overblown, and what the experience suggests about the characteristics of international trade in raw materials and about potentially useful directions for policy.

Postmortem on the Commodities Boom

While the 1972–75 commodity cycle tends to be viewed as a single phenomenon, its separate parts are evident enough and not always causally related. They are worth keeping in mind.

It is of course true that the price rise was about as comprehensive as it was sharp. Each of the major commodity groups showed the effects. With regard to the steepness of the rise, from the beginning of 1972 to the middle of 1974 the U.N. index of export prices of all primary commodities increased by more than 150 percent, fully three times the advance that occurred during the Korean War commodity boom (*2*). With the use of the London *Economist* commodities index, which does not include fuels and is otherwise less comprehensive than the U.N. index, Cooper and Lawrence (*3*) found [illegible] during the past 115 years there has been no year in which commodity prices rose as rapidly as they did in 1972–73 (63 percent) and no 3-year period in which they rose as rapidly as in 1971–74 (159 percent)." Similarly, for a few industrial materials, the sharpness of the decline in prices since mid-1974 has no parallel in the past century.

Nonetheless, the rate, timing, and duration of the advance varied considerably among the major commodity groups. A number of factors, some related to supply and others related to demand, were responsible for the difference in behavior.

In the case of oil, the price explosion did not occur until after the October 1973 embargo. Before that, OPEC (Organization of Petroleum Exporting Countries) demands for higher taxes and a larger share of the total take, which were persistent and successful from 1971 onward, did not cause oil prices to rise much more rapidly than prices of most other primary commodities. Import demand had been expanding rapidly for a number of years—at about 8 to 9 percent a year—principally because of a preference for oil over other energy fuels (due to its low price) and because of the sudden emergence of the United States as a large and growing importer of oil. While world export capacity easily kept up with demand, the oil situation created unusual alarm because of the evidently growing market power of OPEC and because of the contrast with the 1960's, when oil prices declined (*4*).

When OPEC boosted its demands through the almost accidental series of events that began in October 1973, the strong growth in oil consumption and the

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Table 1. Japan's trade in selected industrial materials, 1970–74 and projection for 1975 (16).

Commodity (unit)	1970	1971	1972	1973	1974	1975 (projected)
Aluminum (10^3 metric tons)						
Imports	233	204	271	373	385	271
Exports	3	22	7	2	24	37
Copper (10^3 metric tons)						
Imports	302	268	294	395	293	210
Exports	47	41	26	27	280	31
Nickel (10^3 metric tons)						
Imports	10.1	8.3	12.0	14.3	16.3	7.8
Exports	.4	.2		.2	.5	1.3
Magnesium (10^3 metric tons)						
Imports	2.1	.7	2.9	6.0	12.7	1.9
Exports	.1			.1	1.4	2.6
Tungsten (10^3 kg)						
Imports	106.4	40.3	45.4	204.0	285.5	19.6
Exports	50.6	91.6	81.1	64.2	113.9	232.7
Molybdenum (10^3 kg)						
Imports	114.8	10.3	52.3	196.3	80.5	16.6
Exports	17.5	23.4	21.6	34.7	20.7	19.2
Tantalum (10^3 kg)						
Imports	20.8	11.0	13.7	24.1	34.5	16.0
Exports	2.3	.9	2.3	.5	25.3	15.0
Raw cotton (10^3 metric tons)						
Imports	835	821	867	944	879	718

short run inelasticity of demand for imports put the oil market in a highly vulnerable position. Subsequently, when the market began to shrink, the OPEC countries managed to reduce production so as to prevent sharp competition for markets and a substantial erosion of prices.

Cereals prices also made their quantum jump after a decade of comparative stability, but the causal forces were of an entirely different character. For a number of years, acreage in the exporting countries had been restricted and stocks gradually decreased. Beginning in 1972, crop failures in the Soviet Union, South Asia, North America, and then once again in the Soviet Union levied unusually heavy demands on the world market so that stocks were swiftly depleted and could not be rebuilt (5). Cereals entering world trade amount to only 10 percent of world consumption. In a world with very small stocks, crop disasters in a major consuming country or region can quickly result in uncertainties, tight supplies, and waves of panic buying on international markets. Thus, in response to the various major crop shortfalls of the past few years, cereals prices were the first to peak in the commodities boom and have since fluctuated within a comparatively high range.

For other food commodities the story is mixed. The rapid rise in world income accelerated the growth in demand for sugar and cocoa, with production failing to keep up for several years in succession. By 1974 stocks had fallen to 10-year lows, which led to extremely sharp price increases and then to surprisingly large reductions in consumption and a subsequent fall in prices. (In the case of sugar, a markedly improved crop yield in 1975 also helped to turn the market around.) Coffee prices have been closely related to the depressing effect of a series of frosts in Brazil on world production, and are beginning even now to head toward new highs. In all three commodities a steady decline in stocks made the market vulnerable to unusual changes on the supply side.

On the other hand, for industrial raw materials the price cycle has been dominated by demand. Supply factors exerted a significant influence here and there, as for example the poor U.S. cotton crop of 1974, transportation bottlenecks in Africa and strikes in Chile that reduced exports of copper and tightened environmental regulations that delayed bringing new metal capacity into production. The huge increase in government taxes on bauxite, imposed first by Jamaica and then by other bauxite producers, was also a factor. Nonetheless, the most general and most important causes of the rise and fall of industrial raw materials prices were cyclical: the upward pressures on demand resulting from the unusually rapid growth of the world economy in 1972–73 at rates averaging 6.5 percent a year (1.5 percentage points above trend), and the subsequent collapse of demand following the onset of the worst recession since the end of World War II (6, 7).

Inflationary expectations, exchange rate fluctuations, and sometimes an exaggerated concern about the adequacy of raw material supplies made matters much worse. They were reflected at times in a preference for holding commodities over currencies, in speculative purchases, and in a general buildup of inventories—all of which exacerbated shortages, put sellers of commodities in an unusually strong market position, and fueled the price boom. The subsequent liquidation of stocks when the recession started intensified the collapse of prices.

Reliable data on world stocks of most raw materials are not available, but the importance of speculation and inventory changes is indicated by the remarkable shifts in Japan's commodity trade during the 1972–75 period. Because of the paucity of its resource base, Japan is the largest importer of a number of industrial materials and probably accounts for 20 percent of world imports of this group of commodities as a whole. As is evident from the data in Table 1, Japan's unusually large imports of these materials in 1973 and 1974 show the effects of speculation and panic buying when the boom was in progress, while its exports of the same commodities in 1974 and 1975 show the severity of the subsequent liquidation of stocks. Copper is the most dramatic example, with Japan shifting from being the world's largest net importer in 1973 to a position of virtual balance in 1974. Reactions in Japan to the commodity scare, while probably extreme, were not dissimilar from those in other industrial countries.

In sum, generalizations about international trade in primary commodities can be misleading, as the disparate factors behind the 1972–74 boom attest, and they can also be costly. Eventually it became evident that, contrary to earlier fears, the world did not face an era of permanent shortages, or of a proliferation of effective producer cartels, or of disquieting shifts in political power. In the meanwhile, however, such fears contributed to inflationary behavior, to uncertainty in financial markets and, eventually, to overly restrictive monetary policies and unnecessarily large reductions in output and employment. There were unfortunate political consequences as well. Commodity issues suddenly were on the center stage of relations between industrial and developing countries, pushed there in part because of the unfounded belief that OPEC could be the model for a general restructuring of trade in commodities and the "oil weapon" could be used to bring this restructuring about. Posed in these terms, the issue was almost sure to result in a stalemated confrontation serving principally to draw energies away from more urgent and constructive business between the industrial North and the underdeveloped South.

With respect to the future, what are the

factors to consider in developing a more useful approach to problems arising out of international trade in raw materials? Before answering this question, it is helpful to review the main characteristics of the commodity trade as a whole and the comparative significance of trade in raw materials.

Structure of the Trade

An examination of the composition and origin of world exports is a good place to begin. A breakdown of the major commodity groups and the distribution between all primary commodities and manufactured goods is shown in Table 2 for the year 1973. These data underlie much of the discussion below on the characteristics of the trade.

Oil is unique. By its size alone, trade in oil is in a class by itself. It has been the largest single commodity in world trade for a number of years, accounting for about 5 percent of world exports. After the extraordinary price increases of 1973–1974, the proportion jumped to more than 12 percent. Thus in 1974, oil exports, valued at about $115 billion, were somewhat larger than exports of cereals, oil seeds, and all other foodstuffs put together. As a further comparison, net exports of copper, largest among the raw materials, probably were no more than $5 billion even with the high 1974 prices.

Consequently, the jump in oil prices had an enormous effect on the world economy. The quadrupling of its price represented an income transfer of about 2 percent of world gross national product (GNP) from oil importing to oil exporting countries. Furthermore, the economic shocks resulting from this price boost, coupled with the institutional difficulty of coping with them, probably were the major cause of the world recession in 1974, accounting for about half the decline from trend in world output during that year (*8*).

Other factors, now well known, put oil exporters in a uniquely strong position to manipulate the market. Among the most notable are the slow response of the demand for energy and the supply of energy fuels to higher prices, the concentration of exports among a fairly small number of countries, the strong financial position of those countries, and the comparative ease with which oil production can be cut back in the short term.

Against this background, it is evident that OPEC's market power and the potentially large economic impact of the exercise of that power cannot be used as a model for other commodities. Even for oil, the returns are by no means in. OPEC's cohesion as a producer cartel is only now beginning to be put to a test with the emergence of a substantial surplus between the potential export capacity of the oil producers and world import demand. In effect, the quadrupling of oil prices has set in motion a chain of reactions in the world energy situation; while this response has been slow to develop, its effect on the world oil market will be continuing and cumulative. By its actions from October 1973 onward, OPEC may have traded the advantages gained from maximum use of its market power in the short run for a steady attrition of that power in the medium and longer term.

Table 2. Origin and composition of world exports, 1973 (*17*).

Commodity	Billions of U.S. dollars			
	Developing countries	Non-Communist industrial countries	Communist countries	Total world exports
Agricultural raw materials	9.2	17.4	3.8	30.4
Ores and minerals*	5.1	7.1	1.7	13.9
Food	22.8	51.2	6.9	80.9
Fuels	43.0	13.7	5.8	62.5
Manufactured and processed products	27.9	296.0	36.6	360.5
Residue	1.5	6.9	3.1	11.5
Total†	109.4	392.3	57.9	559.7

*Nonferrous metals—as distinct from ores—are included in manufactured and processed products. †Figures may not add to totals due to rounding.

Raw materials exports are comparatively small. Table 2 shows how fuels (mostly oil) and foodstuffs dominate world commodity trade. By comparison, trade in nonfuel minerals and other raw materials is small. Raw material exports in 1973 were $45 billion, less than one-fourth of trade in primary commodities and 8 percent of total world trade. Of this amount, exports of nonrenewable materials such as ores and metals were only $13 billion.

No item in this group is overwhelmingly large. In 1973, combined exports of the seven largest—copper, cotton, iron ore, wool, rubber, tin, and phosphate rock—probably accounted for about half the total for the group; the other half was spread over 25 to 30 additional commodities, for most of which world exports were under $500 million.

Obviously, shortages induced by marked changes in trade in some of these commodities can create troublesome temporary industrial bottlenecks and sudden jumps in their prices can contribute to inflationary pressures. However, the range of substitutability is considerable and there is also room to shift between primary and secondary materials, depending on price. Generally—again in sharp contrast to oil—even substantial shifts or disruptions in trade in individual raw materials are likely to have isolated, limited, and temporary, rather than pervasive effects on the world economy.

More commodities move from West to West than from South to North. Ever since OPEC's success in oil renewed the world's interest in primary commodities, the issues have been viewed principally as a confrontation between producers in developing countries and consumers in industrial countries. This attitude is reflected in the various actions of the U.N. General Assembly calling for the establishment of a New International Economic Order (*9*) and in the discussions between industrial and developing countries at the first session of the Conference on International Economic Cooperation held in Paris during December 1975. The developing countries, having the OPEC model in mind, see the trade in commodities as a potential mechanism to generate a substantial resource transfer. Industrial countries, apart from taking defensive action, seek assurances of regular and adequate supplies. Both the demands of the former and the concerns of the latter have diminished with the disappearance of shortages and the reappearance of surpluses, but the discussion generally continues as a dialogue between North and South.

Nonetheless, leaving oil aside, Table 2 shows that the major share of trade in primary commodities takes place between industrial countries (including the Soviet Union and Eastern Europe). These countries import more primary commodities (by value) from each other than they do from developing countries. This is true for each of the nonoil commodity categories—foodstuffs (where the dominance of industrial country exporters is exceptionally large), ores and metals, and other raw materials. In the aggregate only 30 percent of the exports of nonfuel primary commodities originates in the developing countries compared to 70 percent in the industrial countries.

This does not make the conditions for trade in primary commodities any less im-

portant for developing countries, since these commodities are the major source of their export earnings. Moreover, a number of developing countries are heavily dependent on exports of a single commodity. Yet developing country exporters predominate in only a comparatively small number of instances—tropical agricultural food products and a few raw materials. For the rest, new trade arrangements would depend as much or more on the support of industrial country exporters as it would on that of developing countries.

Furthermore, the fact that developing countries have widely different interests in primary commodities also complicates the consideration of commodity issues exclusively in North-South terms, or as an across-the-board confrontation between rich and poor nations. Some countries, such as India or Korea, have relatively small interests as primary product producers and exporters. Among some commodities there is a natural competition for markets as, for example, between copper and bauxite or between the beverage crops. Most of all, import costs are a general concern. The quadrupling of oil prices increased the oil import bill of the developing countries not having oil resources by $10 billion in 1974, or by somewhat more than the total amount of concessional aid they received in that year, and it added substantially to the cost of fertilizers and other manufactured products these countries must buy abroad. Thus even when the predominant movement of exports is from South to North, as in oil or sugar, the large majority of individual developing countries have substantial interests as importers and consumers.

Cartel paranoia. Much of the apprehension about the 1972–74 commodity boom centered on cartels: for how many other commodities would producers be able to form effective OPEC-like organizations? Mostly, the concern was about price, but more amorphous fears also existed. Following the OPEC model, would primary producers in a supposed era of chronic shortages withhold supplies for political purposes or, as a variation, might one envisage a grand alliance of primary producers (possibly financed by OPEC) aiming at a substantial transfer of political power?

These latter concerns may be dismissed out of hand, despite the tendency of developing countries to present a united front in generalized discussions of commodity issues in international forums. Apart from oil, there are no primary commodities for which the industrial countries conceivably could be held for political ransom, and in view of the distribution of commodity exports, there is no combination of primary producers that could control the world market and at the same time be motivated to act together to achieve a specific political objective (*10*). As for OPEC financing, most of the oil-producing countries are finding that they have more than enough domestic uses for their oil revenues and none has shown much inclination to supply concessional financing to prop up commodity markets in a big way (*11*).

A somewhat more serious question is whether primary producers can manipulate markets so that over a sustained period of time they can realize prices substantially above competitive levels. The burden of the discussion so far is that what happened in oil tells us little about other commodities, that the structure of the trade indicates that the possibilities for establishing successful sustainable, producer cartels for other commodities are few and unpromising, and that in any event the economic consequences for importing countries would be much smaller than with oil (*12, 13*).

Sustained control over international commodity markets depends on a number of conditions, principally the following: (i) the concentration of exports among a few countries; (ii) inelastic demand for the commodity; (iii) inelastic supply of the commodity or of close substitutes from sources outside the cartel; and (iv) policy cohesion and export discipline among members of the cartel to keep markets tight and prices high. Generally, to fulfill the fourth condition, exporters must be strong enough financially to accumulate stocks and forego current export earnings when surpluses develop.

With the exception of oil, these conditions do not apply to most primary commodities. Among the raw materials, for example, developing countries have a commanding export position only in copper, rubber, tin, bauxite, and hard fibers. Even though exports are concentrated among a few countries, obstacles to the sustained exercise of market control exist, including the weak financial position of most of the exporting countries, sharp competition from substitutes, and potentially large increases in supply from new sources. Apart from bauxite, markets for these commodities suffer from the slow growth in demand. For commodities where collusion between industrial and developing country exporters would be required, differences in policy objectives could be a further complicating factor. Industrial countries, in considering possible gains from collusive action on their exports of primary commodities, must also consider possible retaliatory action against their exports of manufactured goods, which represent by far the largest part of their trade. The general point is that primary producers in a very few instances and for a limited period of time might be able to manage supply so as to raise prices, but their ability to withstand cyclical downswings would be weak and their prospects for sustaining effective price-fixing arrangements over the medium term, let alone the long term, would be dim.

Most of these limitations on the exercise of cartel power were demonstrated during the 1972–75 commodity cycle. During the economic upswing the demand and supply factors cited earlier, rather than collusive actions by producers, were principally responsible for the boom in prices. Once the recession began, producer groups—for example, in copper, tin, rubber, and mercury—could do little to prevent the fall in prices. High phosphate prices have lasted longer because the demand for fertilizer remained strong, but weakness has now begun to set in. Jamaica's imposition of heavy taxes on bauxite, with other producers following suit in varying degrees, comes closest to the OPEC model. However, special factors apply to bauxite since trade takes place mostly within integrated companies rather than on international markets. Usually a company's refining equipment is geared to the use of particular ores and large investments in smelting and refining are hostage to producing country governments. Even so, strains have emerged over how the reductions in bauxite imports induced by recession are being allocated among the producing countries.

A final comment on commodity markets may serve to add a further perspective on the cartel problem. In the past two decades, demand for most primary commodities has grown comparatively slowly and exports have lagged substantially behind the growth in world trade. That is why most of the attention devoted to commodity issues was concentrated on proposals to reduce burdensome surplus and to support prices. The medium-term future at least may not be very different; World Bank studies project a tendency toward softness in commodity markets through 1980 (*12*). These are hardly the market circumstances in which new OPEC's are likely to flourish or which could lead to a substantial shift of power, political or economic, to countries producing primary goods.

Policy Directions

Now that most of the hysteria over commodities has died down, it is possible to take stock and to review options for U.S. policy in a calm atmosphere. Perhaps the

most important lesson to be drawn from the experience of 1972–75 is that there is no single policy to cover the full range of commodity trade problems. To say that the issues must be approached on a commodity by commodity basis is simply the beginning of wisdom.

Two commodities—oil and cereals—bring to the fore the vulnerabilities of the industrial nations to external shocks, either from supply interruptions or from sudden jumps in prices that lead to inflationary pressures and a contraction of overall output. Tropical agricultural products and a few minerals are of special importance to the developing countries. The remaining commodities fall into no special category and for the most part are comparatively small elements in trade or economic life in general.

To begin with oil, the largest of the commodity issues, there is a wide measure of agreement that the vulnerability of industrial nations to OPEC actions must be reduced. This can be done by permitting market forces to encourage domestic production of energy fuels and to restrain demand for energy, and in some respects to supplement those forces by tax incentives or penalties or by regulatory measures. The conflict here is with the requirements for economic recovery, since allowing energy prices to rise too rapidly could introduce major problems of demand management and ultimately losses in economic output. Hence the policy debate over the next few years, as during the past two years, should center on how to arrive at a pace of adjustment that will represent a sensible compromise between the two conflicting objectives. This in turn will require constant modification as more experience is gained about a world of high priced energy and as present uncertainties about the response of energy demand and supply to higher prices are resolved.

If the major industrial nations pursue these adjustment policies on a coordinated basis, with the aim of making gradual but steady progress in containing dependency on imported oil, their bargaining position on the world oil market will improve and the market power of OPEC will diminish. Furthermore, if they continue to enlarge stockpiles and strengthen plans for sharing energy in emergencies (all of which is part of the program of the International Energy Agency) their short-run vulnerability to OPEC pressures will also be lessened. Eventually it may be possible for importers and exporters to reach periodic international agreements on oil, which might permit importers to invest somewhat less heavily in high-cost domestic production capacity and give exporters a somewhat larger market. But this possibility lies in the future, since the present positions of the two sides are far apart and further substantial changes in their underlying bargaining leverage would be required to bring them closer together.

In cereals the immediate requirement is to provide for the rebuilding of world stocks from their present dangerously low levels. Obviously this must await the reappearance of surpluses in world production of cereals. Even then the rebuilding of stocks is not likely to occur on an orderly, systematic, or adequate basis unless the financial burden is shared equitably among the industrial countries, including the Soviet Union, and policy objectives are negotiated and coordinated. Consequently progress in this area will require a major advance in international organization and decision-making. Until it occurs, the industrial countries will face the danger of economic shocks from sudden sharp jumps in food prices and arrangements to cope with food emergencies in the poorest countries will be precarious. Furthermore, there will be less chance of moving toward greater rationalization of world agricultural policies and realizing the efficiencies this can bring. A growing amount of world agricultural trade, on which such efficiencies rest, depends in turn on assured supplies and the sharing of grain reserves in time of reverses in agricultural production.

For those commodities that are exported principally by the developing countries, price stabilization arrangements between producers and consumers could reduce fluctuations in export earnings of developing countries and avoid costly disruptions to their economic programs. Greater price stability also could be helpful to consuming countries and might possibly improve the prospects for a more even flow of investment in the production of primary commodities. However, such arrangements are promising only for a limited number of commodities, and they are difficult to negotiate and sustain. The candidates here include coffee, cocoa, and tin where agreements have already been negotiated, and copper, rubber, tea, sugar, and hard fibers where substantial complications stand in the way of commodity agreements but where the prospects are at least worth serious exploration.

Generally, in such agreements, buffer stocks are likely to be more useful than export quotas as the principal stabilizing mechanism. Agreements based on buffer stocks should be easier to negotiate and, if substantial changes in such stocks are used as a decisive signal for changing the price range, they could permit fairly wide latitude for the use of market forces. Funds to finance buffer stocks should be supplied principally by the industrial countries. It may be more feasible and otherwise could be satisfactory to build such financing into each individual commodity agreement through the imposition of a small tax on

Cereals, one of the two commodities that bring to the fore the vulnerabilities of the industrial nations to external shocks, either from supply interruptions or from sudden jumps in prices that lead to inflationary pressures and a contraction of overall output. [U.S. Department of Agriculture]

the trade. This latter method is in use in the cocoa agreement.

For some commodities—notably among the minerals—where arrangements between producers and consumers prove to be neither negotiable nor appropriate, it would make sense for the industrial countries, on a coordinated basis, to acquire stocks when markets are soft and to dispose of them when markets are tight. This would help to avoid wide swings in prices and investment and would provide some security against price gouging and panic buying in times of shortages. Thorny practical problems exist but so long as the major industrial countries share the responsibility and act according to agreed guidelines, costs are likely to be small and the benefits considerable.

Among the minerals there is also a need to improve the climate for investment in the developing countries so as to assure an adequate and efficient buildup of productive capacity. Investment in the natural resource area is now surrounded by growing political tension, which is partly based on wide differences between host countries and private investors over the size of the prospective economic rents and how they should be shared. As a result, investment capital is being diverted to the exploitation of lower-grade mineral deposits in politically safer countries, with evident sacrifice to the efficient use of resources on a world scale and to the interests of the developing countries themselves (*14*). Here the World Bank and its affiliate, the International Finance Corporation (IFC) could help to ease tensions by becoming a substantial public participant, along with private investors, in politically sensitive investments. In effect the IFC would be acting as trustee for the developing countries—providing disinterested expert advice on what terms of investment are feasible and equitable and assuring these countries, through its policy of reselling its equity position to investors in host countries, of eventual control of the enterprise.

For the large remaining number of commodities, the best policy would be to do nothing, that is, nothing beyond the continuing and rather more urgent effort to reduce tariff and other barriers to trade generally. Primary producers justly argue that the present tariff structure discriminates heavily against the location of processing industries in their countries (*15*). A broad success in the Tokyo Round of trade negotiations, now under way, would reduce or eliminate tariffs on processed products, which in turn would encourage investment in the processing of these products in the primary producing countries themselves.

In sum, a variety of commodity policies, carefully drawn, could strengthen the structure of the world economy and help to reduce political tensions. They deserve sympathetic and urgent consideration, the more so because of the confusion now surrounding commodity issues. This confusion and the atmosphere of confrontation it generates is dangerous precisely because it can destroy the assurance of mutually responsible behavior that is the foundation for a multilateral trading system and the steady growth of international specialization.

There should be no illusions, however, that changes in commodity markets can be a source of substantial resource transfers or otherwise contribute decisively to solving the problems of developing countries. Moderating the economic instabilities arising from the commodity trade will depend more on financial measures, such as a major expansion of compensatory financing measures and of development assistance programs, than on individual commodity agreements.

More generally, the most promising trade opportunities for the developing countries are in manufactured goods rather than in primary commodities. During the past 15 years exports of manufactured goods from developing countries have been growing by 12 percent a year; they now account for approximately 40 percent of the total exports of the developing countries not having oil resources, compared with 20 percent at the beginning of the period. Success in the Tokyo Round could assure that this trend will continue because it would give the developing countries improved access to markets for the growing number of manufactured products in which they are and will become competitive. Furthermore, a reduction in trade barriers would be a powerful means of reducing distortions in international investment and of helping to insure that the benefits of such investments will be equitably shared. All this would provide for real progress toward a more productive international economic order. A preoccupation with commodity problems, or worse, with commodity power and the collection of bizarre ideas that goes under the heading of resource diplomacy carries the danger of diverting the attention of the international community from this essential task.

References and Notes

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2. During the Korean War, the boom ran its course between the first quarter of 1950 and the first quarter of 1951, when prices increased 45 percent. After that prices drifted downward for the better part of a decade until they reached a point about 5 percent below where they were when the Korean War boom started. *International Trade 1972*, General Agreement on Tariffs & Trade, Geneva, 1973.
3. R. N. Cooper and R. Z. Lawrence, *The 1972-75 Commodity Boom*, paper prepared for the meeting of the Brookings Panel on Economic Activity, 4 and 5 December 1975. [The London *Economist* data are shown in the issues of 2 March 1974 and 6 September 1975.]
4. For a careful examination of the factors setting the stage for the oil developments of 1973-74, see J. Darmstadter and H. H. Landsberg, *Daedalus* **104** (4), 15 (1975).
5. In addition, the United States was slow to react to the new situation and delayed increasing acreage, see F. H. Sanderson [*Science* **188**, 503 (1975)].
6. Cooper and Lawrence (*3*), in analyzing the evidence on industrial materials, emphasize the worldwide economic boom and particularly the economic surge in the United States as the major explanation of the price boom of 1972-73.
7. See also *Trade in Primary Commodities: Conflict or Cooperation?* a tripartite report of 15 economists from Japan, the European Community, and North America (Brookings Institution, Washington, D.C., 1974).
8. E. R. Fried and C. L. Schultze, *Higher Oil Prices and the World Economy: The Adjustment Problem* (Brookings Institution, Washington, D.C., 1975).
9. U.N. General Assembly, *Declaration and Program of Action on the Establishment of the New International Economic Order*, May 1974; *Charter of Economic Rights and Duties of States*, December 1974; 7th Special Session, U.N. General Assembly, resolutions adopted in September 1975.
10. Curiously enough, the U.S. export position in cereals is probably the closest case in point, hence the occasional proposals in the Congress and elsewhere to withhold grain exports from the Soviet Union or from OPEC countries to achieve political objectives. Even in cereals, however, potential political linkages are weak to nonexistent, and in any event short lived. Imports are a marginal factor in Soviet grain consumption (10 to 15 percent in a really bad year). For the Soviet Union, a rich country and a superpower, the option of reducing grain needs by reducing meat consumption for a year or so would almost certainly seem preferable to granting significant political concessions in order to buy U.S. grain. Increased Soviet efforts to achieve self-sufficiency would be the main consequence of U.S. attempts to use grain sales politically. As to the member countries of OPEC, grain needs are fairly small and could readily be satisfied from a number of alternative sources.
11. Venezuela made the only known venture in this area when it offered Central American producers short-term loans on quasi-commercial terms so that they would not have to dump their coffee on the market as soon as it was harvested. The United States, the major coffee importer, was prepared to do the same thing, on concessional terms, in 1962. Neither offer was taken up.
12. For essentially similar conclusions and the underlying argumentation see (*7*); B. Varon and K. Takeuchi, *Foreign Affairs* **52** (3), 497 (1974); R. F. Mikesell, *International Collusive Action in World Markets for Non-Fuel Minerals* (U.S. Department of State, Washington, D.C., July 1974); E. Stern and W. Tims, *Am. J. Agric. Econ.* **57** (2), 225 (1975); K. Takeuchi and B. Varon, *Ann. Am. Acad. Political Social Sci.* **420**, 46 (1975).
13. A more alarmist view of commodity cartels has become associated with the writings of C. Fred Bergsten. See, for example, C. F. Bergsten, *Foreign Policy* **14**, 84 (1974); *Challenge* **17** (4), 34 (1974); "The U.S. Must Now Deal with the Other Cartels," *New York Times*, 1 June 1975.
14. See, for example, the discussion of U.S. investment in mining in R. F. Mikesell, *Nonfuel Minerals: U.S. Investment Policies Abroad* (The Center for Strategic & International Studies, Georgetown University, Washington, D.C., 1975), chap. 1.
15. Among the OECD countries generally, duties are either zero or small on most ores and concentrates and substantial on semifinished and finished products manufactured from these primary materials. Japan is the worst offender, but the tariff structure of other industrial countries also discriminates in favor of their processing industries. This practice penalizes the primary producers in efforts to sell processed products in OECD markets. For a clear presentation of this tariff discrimination, see Economic Council of Canada, "Looking Outward: A New Trade Strategy for Canada," (Information Canada, Ottawa, 1975), table 10-3.
16. *Imports and Exports of Japan* (Ministry of Finance, Tokyo, Japan). Japan's imports of metal ores followed much the same trend as its imports of metals.
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Basic Research in Materials

Academic research must become oriented toward possible limitations in materials resources and supply.

Robert A. Huggins

The concern about materials limitations, since World War II, has been interpreted as limitations on the capabilities of engineering structures and devices due to the properties of the materials from which they are constructed, particularly in uses demanding high performance. However, attention is more and more being directed in quite different directions, those in which technology is, or might be, limited by the availability of materials.

The implications of a change in emphasis toward possible limitations in materials resources and supply due to shortage and price are substantial. These limitations have special importance with regard to activities that have large momentum and change rather slowly, such as those characteristic of both the research and educational functions of the university.

This new set of interests presents a major challenge to the institutions whose role it is to provide the fundamental and longer range underpinning to technology. I believe that it is fair to say that the nation's academic institutions are ill-prepared for such a major change in direction, for they have attempted to optimize their activities to meet a quite different set of needs.

In this article I discuss some aspects of the nation's basic research activity and the realities of current "materials" concerns in academia, in order to provide some insight into this problem.

The New Needs

As attention is shifted toward questions of materials resources, it should be recognized that there are two rather different concerns. One has to do with potential shortages or price pressure in the relatively near term, and arises from the nation's recognized vulnerability to the curtailment of supplies, price escalation, or both, in several key industrial raw materials; it results primarily from our dependence upon imports of these commodities from relatively few suppliers.

Potential problems of this sort, which might arise within the next decade, have both technological and political components. Because of the latter, it is difficult to predict the need for, or the type of, specific remedies. It may also be too late for research and development that has not yet been done to have any appreciable effect.

The other major concern involves the ultimate limits of economically feasible resources, regardless of the time scale. One might reasonably expect that research and development could produce positive results in this context, either by working toward objectives which might increase the effective supply of specific materials resources, or by developing changes in technology that might reduce the demand for their utilization. In the latter case, there are only three choices. One can make more efficient use of materials, one can substitute other materials to perform the same functions, or one can lower the technological level of expectation, or standard of living. It is not simple to foresee the role that longer range, or basic, research, much of which is performed in the nation's universities, can play in these arenas without massive changes in both attitudes and activities.

The rapidly increasing interest in questions of materials resources is the second major new wind to blow across the research and development scene in the last few years. The first, of course, was the recognition of the importance of various similar energy-related questions. Energy resource problems have become apparent, and a number of steps have been taken to [illegible]ge the nation's research and development apparatus to deal with them.

As we move into a future in which materials resources may also be severely limited, it is reasonable to expect the nation's basic research community to make a useful contribution. There are a number of important questions, however, about what that contribution might be and how it might be accomplished.

Fundamental Role of Universities

A major role of universities in our society is to provide advanced education to the part of the population that is expected to provide future leadership. An important aspect of this educational process involves the propagation of concepts and techniques with which constructive action can be undertaken. Part of the university function also involves development of these tools and their application to society's needs through research.

The current shift of interest into energy-related science and engineering on the university campuses, while difficult in some areas and impossible in others, is not nearly so traumatic as the potential consequences of a strong shift in emphasis to resource-related activities. The primary reason for this is that there are various energy-related scientific and technological areas that seem to fit reasonably well into what much of the academic research community thinks is of interest and can perform with competence. On the other hand, today's typical academic view is that the technical aspects of questions of materials resources primarily involve existing, if not antiquated, technologies, which are not research-oriented, and which have had less and less contact in recent years with universities. In short, these are not problem areas in which the basic research community has had a role in the recent past, and one is not apparent in the future.

However, it is easy to think that today's way of life is the expected normal and proper one and that any deviation would be inappropriate for a vast number of reasons. But man's memory tends to be surprisingly short, and fundamental changes can occur even in very old institutions in a relatively short time. For example, consider the immense changes that have occurred in the relationship between the nation's universities and the federal government within the last several decades. Except for agriculture (for example, experiment stations) and military training (ROTC), the universities were quite independent of the federal government in this country until World War II.

During and immediately afterward, the important influence of new technology (for example, radar, sonar, rocketry, and nuclear energy) became evident, and the importance of long-range basic research in

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providing the nutrient from which such technological developments can grow was recognized. Long-range federal research support in universities was initiated under the auspices of the Office of Naval Research, and the National Science Foundation was later established with that as one of its primary purposes.

In recognition of the fact that educated people constitute an important part of the technological capital of the nation, the federal research support apparatus was operated in such a manner as to optimize the output of trained scientists and engineers as well as to perform research. This has led to the present situation, in which the graduate programs at the nation's major academic institutions are highly dependent on federal research funds. In fact, such funds support a large number of graduate students in the universities, and changes in patterns of federal funding have an immense influence on both graduate education and university-based research. Such a fundamental shift in the relation between the government and the university was not foreseen even as recently as 2 decades ago; thus we should be somewhat hesitant about extrapolating far into the future.

Current Academic Paradigms

An interesting and thought-provoking analysis of the course of science was presented by Kuhn in *The Structure of Scientific Revolutions* (*1*). One of his major themes is the role played by paradigms, which he describes as accepted models, concepts, patterns of thought, and techniques that define coherent traditions in specific research areas. Successful practitioners in what he calls "normal science" share these paradigms and are committed to a generally accepted set of rules and standards that define both a common body of belief and also a way of looking at and dealing with their particular technical areas. Kuhn observed that an existing paradigm supplies criteria for choosing problems; to a large extent, only work which satisfies these criteria will be recognized by the community as scientifically sophisticated and worthy of being undertaken. Activities in other areas are typically rejected as being metaphysical, the concern of another discipline, or too full of problems to be worth time and attention. Thus, at any given time in a specific field, there are a finite number of problem areas that are considered worthy of attack and sufficiently tractable that they merit attention.

It follows that prestige is allotted in accordance with the current version of the paradigms in a given field. Fashions change, and what is considered respectable and valuable shifts with time. One can perceive the validity of these observations by noting the trends in the selection of Nobel laureates.

Kuhn also pointed out that a scientific community can be constrained and insulated from important problems that are not susceptible to the conceptual and instrumental tools of its current paradigms. In some cases, this can result in an increasingly narrow approach in which finer and finer detail is articulated within a limited range of activities, the discipline feeds more and more upon itself and its self-generated problems with decreasing relevance to the external community.

According to this model, changes to new paradigms occur in science through revolutionary, rather than evolutionary, processes. They arise from the recognition of anomalies in which the existing and generally accepted paradigm fails. A new paradigm emerges; there is a period of conflict between the new revolutionary approach and the previously established articles of faith; and one approach finally becomes dominant.

If one applies this thinking to academic institutions, it becomes apparent that the paradigms that have developed during the last several decades have been such that basic science (as compared to applied work) has carried more prestige and has had a greater payoff in most academic fields. This has been true not only in the scientific disciplines, but also in those nominally called "engineering."

This point of view has been strongly reinforced by federal research support mechanisms, in which peer judgment has played a substantial role. Persons making the decisions, both in and outside of the government, have generally been associated with the scientific disciplines themselves, and they quite rationally aim to see that federal funds are utilized to support research work of the highest quality and relevance—in terms, of course, of the existing paradigms.

It is also not surprising that this internal feedback mechanism results in a concentration of academic research on problems that can be described as opportunity-driven rather than need-driven. In many cases, problems are selected and solved because their solution is feasible or interesting from the standpoint of the discipline rather than because of the external pressure of an applicational need. It is no wonder that turmoil resulted from the sudden imposition of the concept of need-based relevance a few years ago.

What happens in universities has an especially important influence on the establishment and reinforcement of paradigms, for the university's training activities are highly biased by the competition and selectivity resulting from the federal research support mechanism, not just in terms of the specific research undertaken on the campus, but also with respect to attitudes, value systems, and expectations. Neophytes are indoctrinated in their professional paradigms during this stage of their careers.

"Materials" Within the Nation's Universities

The discipline of materials science and engineering has been evolving on university campuses for the last 15 years or so. This process has occurred by the agglomeration of a number of activities previously existing within other more traditional disciplines. After much confusion and contention, it is now evident that materials science and engineering is emerging as a coherent technical field and that a new paradigm is developing.

A major stimulus to this field arose in the late 1950's, when it became recognized that problems involving materials technology constituted serious impediments to progress in a number of areas of great national importance, particularly in atomic energy and technologies related to defense. Special attention was also called to matters related to space and defense because of the appearance of Sputnik in late 1957. Because the properties of materials often limited the performance of devices and systems, the development of sophisticated new devices and systems was dependent on progress in the materials area.

After much deliberation involving the President's Science Advisory Committee, the Federal Council for Science and Technology, and the Coordinating Committee for Materials Research and Development, a long-range interagency program was initiated to provide a special stimulus to the field of materials science. The people taking part in those early studies recognized that the primary difficulty was not merely that more effort in materials technology was needed, but instead, that much of what was being undertaken was lacking in sophistication and effectiveness because it was not sufficiently grounded in adequate scientific understanding of the physical phenomena involved. They also recognized that an important limitation was that there were too few people available with appropriate scientific training.

Three federal agencies, the National Aeronautics and Space Administration (NASA), the Atomic Energy Commission (AEC), and the Department of Defense, agreed to share the responsibility for giving

materials science a push because of its relevance to their interests. One result was a large infusion of funds (about $8 million) to upgrade capital equipment in 79 universities active in materials research. The second, and perhaps more important result, was the initiation of 17 major long-term university programs of a multidisciplinary type. After receiving 76 university proposals, the Advanced Research Projects Administration, acting for the Defense Department, initiated 12 of these programs; the other 5 programs were supported by NASA and the AEC. In each case the purpose was to improve both the quality and quantity of the materials science.

Detailed information on these programs is available (*2*–*4*). It should be pointed out here that the programs and their antecedents have had an important influence in setting the tone of materials research on the university campus.

One especially important development is the recognition of materials science as a generic field. It is now widely realized that significant similarities exist between many classes of materials (for example, metals, ceramics, and polymers) with respect to structure, phenomena, properties, and processes. Emphasis is increasingly being placed on similarities between these classes of materials and the generalizations that can be made about them, rather than their being treated separately.

In addition, the understanding of the nature and behavior of materials has become more sophisticated. This has resulted in large measure from the development of the interdisciplinary aspects of this field. Concepts, tools, and techniques developed in one academic discipline are now being applied in areas traditionally assumed to be the domain of another.

As a result of this program and other influences, the emphasis has been on materials science rather than on resource questions. The current academic interpretation of materials science centers on the relation between the structure and properties of materials as a basis for their design, preparation, and utilization. A recent report (*4*), prepared under the auspices of the National Academy of Sciences, defined materials science and engineering as being "concerned with the generation and application of knowledge relating the composition, structure, and processing of materials to their properties and uses." Although this definition is broad, the important point is that it focuses on properties rather than upon questions of availability, which are the concern of many of the other papers in this issue of *Science*.

The obvious conclusion is that "materials" means something quite different to its current practitioners than it does in the context of this new concern about resource questions. If the nation is going to expect this part of its scientific and technological apparatus to perform a different type of service in the future from that toward which it is currently focused, important changes in course must be undertaken.

Unfortunately, today's typical academic view is that the technical aspects of materials resource questions lie in the domain of fields that, to much of the university community, are considered antiquated, technological (rather than scientific), not oriented toward research, and not really very interesting. To put it bluntly, many people would probably contend that materials science has charged ahead in more science-intensive (high-technology) areas, leaving such experience-intensive (low technology) activities behind in the dust. The record shows that the preparative side of materials science and engineering has long been underfed by federal funds, underpopulated by students, and undersupported by academic administrations.

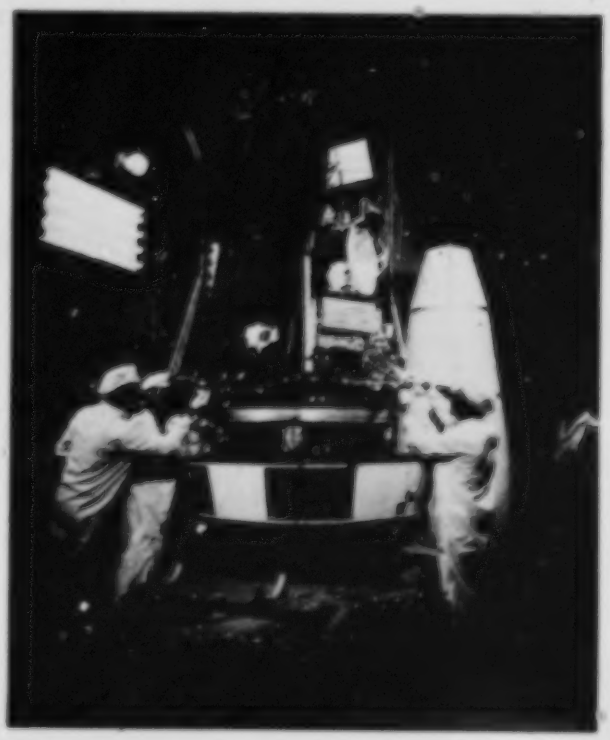
Comments on Future Roles

As has been pointed out above, much of the academic research effort in the past several decades has been oriented toward increasing the depth and sophistication of scientific disciplines themselves. This has also resulted in the development of many new technologies and has been in tune with two very important external influences, the relative availability of federal research funding and the pressure of the job market, which has been heavily biased in favor of the developing (rather than aging) technologies.

During the past 15 years or so, materials science has become a coherent and visible field, and the people in several of the more traditional disciplines are recognizing it as a common base. More recently the major question has shifted from whether materials science will become a stable field, to where it will go in the future.

Much of the growth in activities related to industrial materials has also been in the more sophisticated or science-intensive areas, rather than in those that are more experience-intensive. Industrial growth and the job opportunities for academia's product tend to be where the rate of change is high.

If materials resource concerns do indeed become important, the problem of the reorientation of the basic research community will not be easily solved, because of the momentum in other directions that has been established over the last several decades. However, this problem is not unique to basic research or to universities. It was argued by Hollomon and Harger (*5*) that the concentration of federal research and development funding on matters related to defense, space, and atomic energy has resulted in a reduction in both the magnitude and the quality of industrial research and



With the appearance of Sputnik in the late 1950's, special attention was called to materials related to space. The development of sophisticated new devices and systems was dependent on progress in the materials area. [National Aeronautics and Space Administration]

development related to other (civilian) needs in the economy. They contended that in addition to the bias exerted directly by selective expenditures of funds in certain areas, there was economic competition for available trained personnel, which tended to concentrate most of the effective scientific and engineering personnel in those fields receiving greatest federal support. They, among others, have pointed out the serious decline in our relative competitive position in an area in which this country used to be paramount—general industrial productivity.

Contrary to the conventional wisdom, it is now apparent that, in many important cases, the major reason for the encroachment of Japanese and European technology upon traditional American markets is not directly related to hourly labor costs. Instead, it is often due to increased sophistication and productivity in industrial products & technology. Governmental policies and practices can have a large influence upon the disposition of available resources, including the technical labor force (6).

With regard to basic research and the university role, there are things that can be done to begin to utilize this set of national assets to alleviate some long-term materials resource constraints. It will be important, however, to focus on the optimum use of existing strengths, rather than to precipitously dismantle the apparatus that has been established for the successful pursuit of other goals. We should carefully think through the types of activities that can fit well into effective patterns of university, as well as industrial, action, rather than rushing off to make basic changes in our institutions.

Development of useful alternatives over the long run is much more than simple substitution among existing resources. In order to have more than a transient impact, we need to understand where, and more importantly, why, important materials are currently used. Knowledge of their functions (in fundamental terms of the structure and properties of the materials employed) in devices and of the various phenomena that control them will be important.

These questions are, of course, near the heart of the current paradigm in materials science; if this information were elucidated, sophisticated materials engineering might develop alternatives with the same property-related function as the commodity whose availability is under question.

It is imperative that we encourage increased attention to such matters by the nation's universities in such a way as to build upon existing strengths. Part of the problem will certainly be to interest and excite a community that has been oriented in a different direction and marching to a different drummer.

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Materials Supply: The Impact of Human Institutions

James Boyd

The industrial base of a modern technological society requires a vast array of raw materials, supplied in innumerable, constantly changing forms. This society provides its people with ample goods and services, only because it manages to secure adequate supplies of such materials as iron, steel, aluminum, copper, and phosphate. And contrary to recently proposed theories, the supply of these raw materials depends more on a succession of interrelated human institutions than on the resource base itself.

Throughout human history increasing numbers of substances have been discovered and more specialized needs have developed. These materials require reduction into useful states, they require mining or harvesting, concentrating, smelting, processing or refining, alloying or compositing, and fabricating before they become useful to society. Thus, sophisticated materials usage has mandated the formation of equally sophisticated human institutions; such an evolution formed the basis for the industrial revolution, which is still occurring.

Nature provides the basic resources; through a network of human endeavors and activities man discovers the needed minerals and converts them to the quality and form required by society. Man-made facilities produce the materials to meet the functional needs of society. Farms, harvested forests, mines, and oil wells do not spring "full blown from the brow of Jove." Rather, the basic resources that support the diverse materials-supplying activities must first be discovered through exploration. After discovery, they must be developed through such institutions as the capital market and corporations and through government policies. In the world of minerals, resources that can be converted, economically, into useful materials must be discovered and defined. Such resources, which form the foundation for economic progress, are termed reserves.

Reserves—circumscribed by location, quality, and economic viability—are finite. Further, they occur irregularly around the globe. Thus, no locality, state, or nation can be self-sufficient in all of the materials it needs or wants. Throughout history, this resource distribution problem has caused many wars. The development of transportation and trade has ameliorated but not eliminated this conflict in recent centuries.

Industry and consumers select and use materials on the basis of their ability to perform desired functions, and few desired functions cannot be performed by two, if not many more, different materials. The basic operation of society, therefore, does not depend on one or even several materials. As demands tax the ability of one commodity's resource base to supply all requirements, either new reserves evolve or more abundant materials emerge which can perform the required function. This process of supply involves continual dis-

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covery of new economic resources, advanced technological developments, and changing patterns of materials usage. It is a highly complex process indeed. Because of the dynamic nature of materials supply, the total resource base, when related to the foreseeable needs of mankind, looms extremely large. Therefore, while the cornucopia theory of limitless resources does not stand firm, the premise of material limitations impeding human advancement offers equally little validity. The principle of materials interchangeability, which expands the resource base, points to the use of human ingenuity and institutions to meet the needs of society.

Institutions of Discovery

The supplies of natural fibers being produced on the surface of the earth may be inventoried by modern aerial and earth satellite techniques. Eventually the rate of growth, the health, and the distribution of these renewable resources will be determined readily in this manner; the basic plans for their exploitation may then be made in an organized fashion to ensure the resource base for the world's total supply system. Because of this ease of discovery, the resource base of the natural fibers need not be discussed further in this article. The more difficult questions, which we must consider, revolve around minerals discovery.

The prospector, the original minerals explorer of the United States, is a familiar figure to all Americans. But the surface of the earth, in its accessible regions, has long since been examined very thoroughly; now the discoverers of minerals must search in more remote areas and at much greater depths. They must find nature's treasures in more secure hiding places. For discovery to proceed, government must make accessible, to the raw materials producers, lands that offer potential sources of future mineral reserves.

Modern science has developed many new tools to aid in the search for concentrations of minerals in the earth's crust. Thus, the explorers of today may start with data obtained from satellites, continue exploration by use of sophisticated instruments that can be flown closer to the surface of the earth, and proceed with geophysical and geochemical studies at the surface of the earth. All of these technological developments add to our ability to gain knowledge about the earth's crust; they supplement the geologist's limited visual capabilities. These tools aid in the art of exploration, which remains an art because the geologist necessarily operates in an inexact science.

Geologists then prove or disprove their theories by actual physical observations, by making tunnels, shafts, or drill holes. These hard slogging field techniques either yield a new reserve, demonstrate a temporarily uneconomic resource, or reveal the barren character of the prospect site. Of 10,000 conceptual deposits isolated by geologists in their initial examination of an area, only 1,000 will merit the application of such scientific exploration activities as detailed geophysical and geochemical examinations. Perhaps 100 will then be worthy of more extensive drilling, trenching, tunneling, or shaft sinking. Of those 100 sites, only 10 will warrant the major expenditure of funds to sink shafts, tunnel, or drill in detail. And of those 10 sites, evaluated so thoroughly, the odds are that only one will be immediately turned into a producing mine. Despite the development of many fine scientific tools, which yield invaluable data, exploration remains a very expensive and highly risky operation. The discovery of mineral deposits sufficiently concentrated by natural processes in the earth's crust is far from a sure proposition.

The cost of this risk becomes an institutional issue. Originally, when taxation was a minor factor, the ability to retain profits was sufficient incentive. As taxation became a dominant factor in project evaluation, most governments compensated for it either by making land available for exploration at little cost, by permitting the costs of exploration to be deducted as an operating expense against other corporate or individual income, or by rewarding risk-taking through certain tax mechanisms. Some governments permitted the eventual producing mineral operation to include in its cost, for the purpose of tax calculation, a percentage of its earnings; this tax mechanism is the depletion allowance, a form of depreciation applied to a wasting natural asset.

To attract sufficient money to support exploration activity, risk must be rewarded. The degree of reward, in large measure, must equal the degree of risk. If, for example, a successful mineral exploration project produced an economic entity that earned, for its investors, no more money than a savings account, that project would not get capital support. No one will undertake a risky enterprise unless he is assured that he will have possession of the asset when it is developed, and will be permitted to make more than the normal profit expected from a secure banking or manufacturing enterprise. But, in recent years, there has emerged a tendency to assume that the rewards for risk-taking in the discovery and development of mineral resources are unconscionable profits, and a burden on the rest of the population. Thus Congress and administrative agencies applied heavy royalty cost, withdrew federally owned tracts from prospecting under the mining laws, and eliminated the percentage depletion allowance for petroleum. Government, in making such moves, severely constrained the ability to discover new resources of minerals to meet the needs of society.

If industry is to provide society with raw materials from the earth at the lowest possible cost, it must be permitted to find deposits that can be produced most economically, given the current state of technology. Alternatively, exploration and development could be undertaken by government itself. I will not try to debate these alternatives here, but will leave it to the reader to visualize the reaction of a public servant in charge of the expenditure of public funds when he faces the enormous risks involved in the process of minerals discovery. Government employees traditionally orient themselves toward security rather than risk in the discharge of their public trust; to commit a risk-oriented program to such individuals might well ensure a scarcity of supply—and in short order.

Thus, the first activity in the chain of materials supply involves a diverse group of human institutions devoted to identifying natural resources that can be used to benefit the economy. Included are individual prospectors, corporate exploration departments, and corporations engaged, almost exclusively, in the exploration process. Geophysical companies apply specific remote sensing techniques; they assist geological organizations in finding geological conditions favorable for the concentration of materials. A variety of financial institutions support these activities. Certain government agencies provide access to some lands with potential resources; others provide financial incentives for undertaking these ventures. Additional government organizations use actual dollars to provide basic geological data. The delicate balance between these groups, and a favorable political climate, must be maintained if exploration teams and prospectors are to continue to maintain a reserve base.

Institutions of Supply

When a deposit has been identified as a reserve, it is next necessary to develop it into a productive property. This may involve preparing the surface of the land to permit the establishment of an open-pit mine; it may require sinking shafts or driving tunnels to expose and outline the ore body and to prepare an underground mine for production. Development includes construction of mills to separate the waste ma-

terials from the useful constituents of the ore and facilities to dispose of the waste. Concentrated minerals are seldom in the chemical state in which they are used. Smelters and refineries must be built to reduce the valuable minerals to useful metals or materials. Finally, the process of supply mandates the construction of additional plants to shape the raw materials to the exacting demands of modern technology—to draw wire, roll or extrude metals, and put them into the form in which they are eventually utilized.

The system of mines, mills, smelters, refineries, and fabricating plants requires vast expenditures of capital. These capital demands dwarf those normally associated with manufacturing; the gross capital investment and the capital investment per worker are on a scale not contemplated by manufacturers of plastics, textiles, or other products in the manufacturing sector. For example, the minimum investment to construct a new magnesium plant approaches $75 million. Building an integrated complex to produce 125,000 tons of aluminum per year requires $283 million. The construction of an integrated steel complex to produce 4 million tons per year costs some $2.4 billion. That investment represents 3 percent of the present capability of the aluminum industry and 4 percent of steel capability. These data, supplied by the U.S. Bureau of Mines, demonstrate the enormous problem of marshaling capital resources to the materials supply industry (*1*).

The first institution related to the materials supply, then, is the financial market. The Chase Manhattan Bank estimates that some $90.5 billion in capital will be required by the metallic minerals industry between 1974 and 1978 (*1*). The National Materials Advisory Board of the National Academy of Sciences estimates that the steel industry alone will have to invest $3.5 billion per year for the next several years (*2*, p. 83). These prodigious amounts of money may be raised through the traditional financial (stock and bond) markets or borrowed from lending corporations.

Commercialization also involves the engineering consulting firms that provide the technological knowledge needed in the construction and operation of new facilities. These firms design new facilities to take advantage of the latest technical improvements. Virtually all minerals plants built today are based on new technical discoveries, inventions, or developments made since the last plant was built. Factoring these new technologies into facility planning requires a core of trained and competent scientists and engineers. It also requires a knowledge of the markets for minerals throughout the world. In all but such low-cost materials as sand, gravel, and limestone, prices are set by world markets, even though they may be controlled in part by individual governments or collections of governments. Therefore, a whole gamut of institutions in many nations must be involved in the basic raw materials industries if the requirements of an industrial world are to be met.

Supply Shortages and Institutions

Human emotions are fleeting, and memories very short. History remains unread, its lessons forgotten. For many years authorities had been predicting that exponential growth rates in consumption of materials and energy could not last forever. Shortages would occur unless corrective actions were taken. But it took long lines at gasoline stations, and seemingly endless delays in the delivery of goods, to bring the point home. In the same way, streams and atmospheres had to be visibly polluted before society perceived a need for changes in population growth, wasteful habits, and extravagant life-styles. Today much of this is forgotten; materials appear to be in copious supply to meet our depression-invoked diminishing needs. The urgency has gone out of the pressure to correct the fundamental forces which result in shortages.

In the meantime the environmental concerns brought the urge to change the course of society—immediately. Government demanded the expenditure of vast sums of money on equipment that would produce no product and generate no revenue. Neither the resource base nor the total environment demanded radical and sudden changes; further, the diverse organizations affected by those demands lacked the extreme flexibility needed to cope with abrupt departures from a tradition of meeting the economy's needs. These new demands shattered the delicate balance between institutions that participate in the processes of discovery and supply. Too much correction of one apparent evil resulted in far more damage to that balance than the physical deficiencies warranted. Savings, the only true source of capital, were forced into channels unresponsive to the marketplace.

Rapid application of environmental and safety regulations requiring costly investments in equipment and facilities that produce no product and are often beyond the financial capability of private industry. These problems are intensified by frequent changes in the regulations, which require further capital investments (*2*).

No matter how important environmental, safety, and health problems are, too rapid a diversion of capital results only in serious damage to the very operations that can correct the deficiencies.

In order to build facilities to protect the environment and improve health and safety the industrial base must expand, or our standard of living and our progress toward alleviating poverty will be degraded. Reduction of incentives to take economic risks and too rapid divergence of funds to worthy, but unproductive, goals have impeded the flow of capital to those institutions—the corporations—which supply the materials and erect the facilities to ensure both adequate materials supply and environmental protection. The delicate balance between the numerous institutions affecting materials supply must be reestablished.

Government Institutions

Among the institutions involved in bringing materials from the ground to use in society, government, the educational system, and the professional societies enjoy the most ubiquitous positions. They affect the process at all stages and in a broad variety of ways. Thus, these three organizations merit some specific comment and analysis.

Because the materials industries affect all aspects of society, and because almost all impacts on the environment result from the production, treatment, and use of materials, it is necessary that these industries operate within certain clear-cut rules. Their regulation emerges, largely, as a governmental function, for protecting both the environment and the total supply base is not a natural marketplace activity. Further, many costs associated with protecting the environment cannot be met by any one industry or group of industries; that conclusion was reached by the National Materials Advisory Board (*2*, p. 3). Thus, if the costs of providing a raw material base and protecting the environment are to be borne, they must be borne by society as a whole. And society's mechanism for accomplishing these tasks is its government.

The ultimate users of raw materials, the consuming public, seek satisfaction of their needs and wants. Therefore, an essential part of government policy is to ensure that the costs of protecting the environment become a part of the costs of production. Only then will the costs of environmental protection be borne by the ultimate users of natural resources. Unfortunately, Congress perceived a simplistic solution to this perplexing public policy question; it created a government agency with a single objective, resulting in activities affecting one phase of the total system without due

regard to all others. Institutional imbalances resulted, disrupting the normal flow of materials to the consumers.

Government sets the ground rules within which private corporations undertake their responsibilities to society. It is essential, therefore, that the regulating agencies be operated in such a way that they provide stable rules under which the marketplace reflects the costs of common goals to the consumer; in many cases these inflationary impacts are unnecessary. Thus, the operation of government must be brought into balance with the operations of financial and corporate entities.

Educational Institutions

None of the institutions involved in materials supply can operate properly without employing individuals trained to understand the ramifications of technology, the financial structure of the marketplace, and the natural conditions under which these forces operate. This returns us to the fundamentals of our educational system. The acquisition and application of knowledge undergirds our entire society, our entire economy. And the institutions of higher learning serve both functions. Further, they serve as the basic knowledge transfer points.

Widespread and sound education remains fundamental to the understanding of our materials supply system. As the sum of our knowledge continues to increase, society must learn far more facts and understand many more principles and concepts. The development of sound thought processes in the young is critical to the health of the public and private structures involved in the production of raw materials. In that, the needs of the materials supply community do not differ from those of the other groups in society.

Today, because of the information explosion, young people find it increasingly difficult to achieve the level of knowledge necessary to accept responsibilities in human society with only secondary school backgrounds. Even those with college training may encounter serious problems. Professional responsibility frequently requires additional preparation. We have, therefore, built up engineering schools, advanced business schools, law schools, and graduate schools of science; these organizations train the minds of those who will eventually command much of our nation's productive activity. The educational institutions must nurture, protect, and advance the one most important resource—human intelligence.

Professional Societies

Scientific and professional societies evolved in the process of industrialization, both here and abroad. In these societies, individuals engaged in the same field exchange views and motivate each other to think more precisely about the solutions to broad or specific problems. They enjoy strong linkages with the universities—the custodians of the development of human knowledge. These professional associations stimulate the thinking that leads to developments based on the latest technological discoveries.

Some deride the American system for apparent overorganization; nevertheless, American professional societies continue to lead in the advancement of scientific and engineering knowledge. The technological community in this country and throughout the world benefits from the deliberations of American professional societies. Engineers and scientists engaged in education, industry, and government can assemble to discuss new developments in specific fields of endeavor. These discussions improve the operation of such specific disciplines, and of science as a whole.

The National Academy of Sciences, involving science, engineering, and medicine, is among the greatest professional societies created. Various agencies of the government can approach the Academy, which is as unbiased as human institutions can be, and gain its consideration of scientific subjects. Institutions such as the Academy are served entirely on a voluntary basis; they collect, in one place, many of the most knowledgeable minds available on any specific subject. They seek to come as close to the truth on any particular branch of knowledge as is humanly possible. If government institutions understand and accept their advice, our political system may work more efficiently.

Conclusion

Material supplies are the food on which an advanced technological economy and society lives. Natural resources, from which materials are derived, form the base of all material wealth. To further the goals and ambitions of any society, it is essential to provide access to that base at the lowest possible cost and to encourage its development. Each step in the supply chain, beyond the discovery of resources, is a multiple of that first cost for exploration and development of minerals. And the distribution of wealth is a function of the availability of materials to all those who need them. Bringing about this availability of minerals remains a problem of producing financing, government, and educational institutions.

The materials supply industries must operate smoothly if society is to function adequately; this efficiency of operation remains critical to the functioning of society because of the pervasive influence of minerals and fibers on human activity. Thus, the many institutions affecting materials supply must be operated in consonance and harmony. The imbalances caused by severe restraints imposed by one human structure on another, no matter how necessary, clog the gears of supply. The costs to repair institutional imbalances are inevitably borne by society's poorest members.

Because of the inextricable interweaving of human activities affecting materials supply, and the balance that must be maintained between these human organizations, knowledge and its application become premium considerations. Constraints, such as those necessary for protection of the environment and worker safety, must be applied by specialists who take advantage of the best knowledge available to them. These constraints must be developed to be responsive to all of the needs of society, rather than the specific desires of relatively small social groups. Further, since almost all human institutions affect the availability of materials, each organization must develop an awareness of the broader implications of its activities when it seeks to influence a specific segment of the materials supply system.

Abraham Lincoln stated in his Second Message to Congress: "The dogmas of the quiet past are inadequate to the stormy present. The occasion is piled high with difficulty, and we must rise with the occasion. As our case is new, so we must think anew and act anew. We must disenthrall ourselves, and then we shall save our country." Although the crisis he addressed differed from the present problems of materials supply, the attitudes he encouraged for this country remain germane. We must constantly think through our actions, and bring to bear the latest knowledge, if we are to assure a continuity of societal health and progress—economically and socially. We must constantly make our institutions responsive to our needs, and among those needs is materials supply.

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The Evolving National Policy for Materials

Our future materials policy needs a much broader interpretation of the national security.

Franklin P. Huddle

This article traces U.S. materials policy since World War I, characterizes the abrupt change in the status of materials in the mid-1970's, and discusses contemporary approaches and concepts that respond to this change. The article concludes that national materials policy-making in the United States has been a succession of fragmented, incoherent spasms. There has been no awareness of the sweep of events over a long period in the past, and little concerted attention to future prospects.

Materials policy is complex because it is affected by different groups with different problems and different options to achieve the range of objectives. There is no way that national policy can fully meet all national needs. Only the U.S. Congress, an institution designed to provide political solutions through compromise, is equipped to mediate the conflicting claims on national policy in this essential field. But the Congress requires authoritatively and objectively analyzed technical information and data on supply and demand and on the economy, to chart a policy for the future.

Herein, I define materials as "stuff that things are made with." Materials have a "life cycle" from extraction to refinement to processing to fabrication to use in finished products and thereafter to discard or recycling. This sequence is called the "materials cycle." National materials policy is "the identification of those aspects of the total materials cycle for which concerted national actions will probably serve the public interest, and the prescription of what these actions should be" (*1*).

The industrial development of the United States can be divided into three epochs; the extractive extended from the earliest colonial period to about 1900, that of manufacturing ended about 1960, and that of services began about 1960.

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The Extractive Period

Despite the program initiated by Alexander Hamilton as first Secretary of the Treasury to promote manufacturing, factory labor did not outnumber farm, mine, and forest workers until almost the close of the 19th century. The early emphasis on the extractive industries assured that, with the rise of the factory economy in the 1800's or so, the abundance of food, fiber, ore, and fuel conveyed the durable impression of limitless natural resources to sustain industry. The United States, therefore, easily met its expanding industrial requirements while also exporting large quantities of coal, petroleum, and metals.

A first indication of waning abundance came after entry of the United States into World War I. The sharp increases in demands for raw materials in 1917 and 1918 brought shortages in parts of the country later specified in the "Harbord List." Reorganization of the War Department in 1919 included the establishment of an industrial mobilization planning unit in the Office of the Undersecretary. In this office, a list was prepared in 1921 by Colonel Harbord of 28 materials that had presented supply difficulties during the war (*2*). However, much of the difficulty with shortages during that war came from the confusions and inexperience with planning for military requirements. (Huge demands were forecast and production well underway to support a fresh two-million-man army for a planned 1919 offensive at the time the war ended.)

The Manufacturing Period

World War I accelerated a shift in emphasis from extractive to manufacturing industries. In the 1920's, manufacturing became clearly dominant in the United States. While the production of food, fiber, fuel, and minerals continued to rise, the number of workers in these industries declined steadily; meanwhile, manufacturing became the primary occupation of U.S. workers. Despite management emphasis in the 1920's on labor productivity, the growth of manufacturing industry required a continuing increase in the work force, as well as increasing quantities of an ever-widening list of industrial materials.

The two decades that followed World War I were a period of boom in the 1920's and bust in the 1930's. New discoveries of petroleum and further exploration of western coal and copper deposits conveyed the impression of limitless natural wealth. The United States was the leading exporter of copper in the world. But in the 1930's, the Great Depression brought a sharp dip in demand for products and materials. Factories, steel mills, copper refineries, and coal mines went idle. At the depth of the depression, copper hit an all-time low price of 4.7 cents a pound and the state of Arizona began to use it to make automobile license plates. Much New Deal legislation was aimed at making raw material surpluses manageable.

However, a little-noticed trend was occurring during these two decades. Technologists in England, Germany, France, and the United States were engaged in a search for ways to enhance the properties of the basic materials (steel, copper, and aluminum) with alloying additives (nickel, chromium, manganese, vanadium, molybdenum, zirconium, and tungsten). New or increased uses were found for organic materials (rubber, copra, palm oil, kapok, tung oil, pyrethrum, and many others). Uses of other nonferrous metals (tin, lead, zinc, and magnesium) expanded. Exotic metals like beryllium, uranium, and columbium (niobium) found specialized industrial uses, as did nonmetallic minerals like mica, quartz crystal, graphite, talc, and asbestos. When World War II began, in September 1939, all these materials and many others went to war. That war, fought over a wider geographic spread with a greater mobilization of troops and resources than World War I, called for a vast range of new kinds of hardware and sophisticated technology. A list of materials that presented supply problems in the war, prepared by the staff of the Army-Navy Munitions Board (*3*), numbered 298 items and was probably incomplete.

The United States entered the war at the end of 1941, proposing once more to serve as the "arsenal of democracy." Excess industrial capacity was put to work on war production. Mines, mills, and smelters worked overtime. New petroleum pipelines were built to bring fuel to war industries. A $750-million synthetic rubber industry was

built from scratch. Many new materials came into importance as radio, radar, and sonar became more sophisticated. Primitive gas turbine engines created a small but growing demand for high-temperature alloys. The $2-billion Manhattan District project called for substantial quantities of beryllium, high-purity graphite, and stainless steel. Tungsten carbide was used in enormous quantities in antitank ordnance. The capacity to refine aluminum and magnesium was greatly increased to build President Roosevelt's promised 50,000 planes a year.

Immediately after the war, a new "Strategic and Critical Materials Stock Piling Act of 1946" became effective. Its purpose was to reduce or eliminate a "dangerous and costly dependence" of the United States on "certain strategic and critical materials" essential in a war emergency. The program would accept transfers of war surpluses, purchase in the market, and secure on long-term contracts the materials needed to complete these objectives. The act also instructed the Departments of Interior and Agriculture to conduct research in ways to develop and extend supplies and to find substitutes for strategic and critical materials.

As the inflationary pressure of pent-up consumer demand after World War II was beginning to lose its force, the Korean War broke out. The impact of this conflict on U.S. industry was notable. While the theater was not large, heavy use of helicopters, combat aircraft, and artillery consumed substantial quantities of strategic and critical materials.

In addition, the fact that the conflict was initiated by a communist regime was interpreted to signify that aggressive action by force of arms to extend the sway of "international communism" in Korea was the product of deliberate policy by "World Communism" and that further aggressions were to be expected elsewhere. To anticipate and deter this perceived threat became the main line of U.S. policy; it entailed restoration and mobilization of U.S. forces, reequipment of the Navy and Air Force, reopening of defense plants, construction of new industrial facilities, arming and equipping of U.S. allies in Europe and elsewhere, and an ambitious program of materials stockpiling. These activities coincided with the peak of Marshall Plan assistance to war-devastated European nations and other foreign aid programs, and the outflow of U.S. goods abroad stimulated a new wave of consumer demand in the United States. By 1952 U.S. production of manufactures was about half the world's, and industrial consumption of materials reached similar proportions.

It was during the Korean War years, 1950 to 1952, that the Paley Commission prepared its historic report, *Resources for Freedom* (*4*). The commission was impressed with the rate at which U.S. materials resources were being chewed up. Arkansas bauxite was nearly exhausted. The rich Mesabi iron range was about gone. Imports of materials necessary for U.S. industry were rising generally. This country had become one of the world's largest importers of copper. And the demands of new technology were enlarging the list of essential imports to include such items as palladium, tantalum, cobalt, hafnium, and especially uranium.

Extrapolation of statistics for future U.S. materials requirements based on trends over the years 1947 through 1951 gave a frightening picture of exhaustion and foreign dependence. On the other hand, extending the figures of per capita consumption in the United States to the rest of the world suggested that total world exhaustion of many materials would not be long delayed.

Accordingly, the Paley Commission urged four national measures: (i) statistics on the relation of the supply of materials to the demand should be carefully maintained and closely watched; (ii) resource conservation and development should be pressed, with emphasis on new materials technology in substitute materials; (iii) a nongovernmental institution should be established to monitor the state of materials supply and demand; and (iv) a new governmental institution close to the President should be established to formulate and direct national materials policy.

The Paley report was released in June 1952, during the closing months of the Truman Administration. National attention was focused on the presidential campaign during the rest of that year, and little effort was devoted to implementing the recommendations of the report. Studies were made by the National Security Resources Board (NSRB) (*5*) and the U.S. Munitions Board (*6*) on implementing actions, and the NSRB report was duly transmitted to Congress. However, as the Korean War subsided, mobilization programs tapered off, stockpile goals began to be achieved, and demands for materials eased. The mining industry, tuned to expanded wartime demands, found itself once more producing surpluses. The plight of this industry confronted the new Administration in 1953.

Materials policy between 1946 and 1953 had centered on mobilization readiness through stockpiling and conservation. The rationale of this two-part policy was to hold essential requirements to the bare minimum by conservation measures and to build reserve stocks to meet the needs of an expanded war situation. Appearance of postwar surpluses called for a change in policy.

On 26 October 1953, President Eisenhower appointed a Cabinet committee to inquire into national policies affecting the production and utilization of metals and minerals. He also stressed the need for balance between domestic mineral development and assured access to overseas supplies for peace or war, implicitly calling attention to the plight of the domestic mines. At a meeting of the Cabinet in March 1954 it was decided that the national stockpile should be enlarged to provide a market for the depressed domestic mining industry, with particular reference to lead and zinc. (The price of lead rose 20 percent and that of zinc 24 percent during the next 9 months.)

On 30 November 1954, in a more formal set of recommendations, the Cabinet committee called for a substantially enlarged stockpile "to meet the tremendous surges of demand that come with war." It noted that existing stockpile objectives were minimum objectives, based on substantial wartime imports and stringent conservation measures. Accordingly, it recommended supplemental long-term objectives to reduce or eliminate foreseeable wartime shortages, reduce dependence on imports, and eliminate the need for extreme wartime conservation measures.

The committee went further. Minerals were of two classes, those produced in the United States and those imported. Determinations of supply and demand should be made on a case-by-case basis, and comprehensive programs should be mounted to expand domestic capacity to maintain production, plus an "intensive search for new deposits and development of new properties. . . ." It called for easing taxes and giving financial assistance for mining activities, improving discovery technology, more vigorously exploring for minerals, revising mining laws that restrict exploration, improving collection and dissemination of data on minerals, studying ways to improve utilization of minerals, and coordinating the government with the mining industry. Planning would be based on a 5-year war, as urged by the Department of the Interior, instead of on a 3-year war which the Joint Chiefs of Staff preferred as a basis for stockpile objectives. In addition, the principle was adopted that the stockpile should contain enough of each material to meet one full year of normal use (*7*). In brief, the new policy combined the earlier concept of a war reserve with a new concept of underwriting the market for surplus minerals produced domestically and subsidizing new domestic

sources of minerals, all on a case-by-case basis.

As the economy sagged in the closing years of the decade, this policy had a mixed effect on the economic health of a number of domestic mines. The expanded stockpile benefited some mines. However, the policy also led to the accumulation of worthless and inaccessible low-grade chromite at the Stillwater, Montana, deposit, procurement of domestic tungsten at four times the world price, and a large accumulation of copper.

Perhaps most important, the purchases of several metals at elevated prices by the stockpile drew U.S. metal off the market while foreign producers filled the gap at the attractive supported prices. Thus, when the national stockpile objectives were reached and buying stopped, prices fell. The intent of the program had been to stimulate a healthy and productive domestic mining industry but few of the new mines thus "stimulated" remained open after the bonanza ended. Reliance on imports of metal continued to expand thereafter.

When John F. Kennedy became president, national materials policy underwent another review, this time by the Congress. To conduct this review, the President turned to Senator Stuart Symington (D Mo.), who earlier had been chairman of the National Security Resources Board (NSRB). A week later, the President created the Executive Stockpile Committee "to review the principles and policies which guide our national stockpile . . ."; the chairman of the committee was the Acting Director of the Office of Emergency Planning (successor to the NSRB).

The Senate investigation was retrospective; that of the Executive branch dealt with future policy. Both groups agreed that stockpile secrecy had been excessive, that objectives should be simplified, that stockpile accumulations were unbalanced and for some materials far beyond reasonable levels, that military opinion as to the duration of a future war should govern the setting of objectives (that is, a 3-year war rather than a 5-year war, but also the possibility of a number of small wars), that provision should be made for reserves under conditions of a nuclear war, and that stockpile purchases to support domestic mining should be abandoned. One addition to policy, suggested by the Executive Stockpile Committee (*8*), was that in setting stockpile objectives, consideration should be given to "the possibility that in a mobilization situation short of war, sources of raw materials may be denied to us."

In its final report in 1963 the Symington Subcommittee was sharply critical of the domestic purchase programs of the stockpile (*9*). These had been justified, the report said, as "in the national interest to develop and maintain a mobilization base for certain highly strategic materials." But "the hearings showed that, without exception, the domestic purchase programs failed in the attainment of this objective."

A separate policy study had been commissioned in 1962 by E. A. McDermott of the Office of Emergency Planning, to be performed by a group of consultants under the leadership of W. Y. Elliott of Harvard University. This group prepared a draft report titled "Materials Availability for the Free World," which was widely circulated within the government but never made public. At a colloquium at the American University, 24 November 1964, Elliott and his associates summarized some of the findings of the study (*10*). He called attention to the neglected roles of science and technology in generating new requirements for exotic materials and in devising techniques of conserving and extending materials supplies. He warned that indiscriminate dumping of stockpiled materials would injure world markets. He urged retention of stocks as a cushion against manipulation of the supply of materials as a consequence of "guided revolutions" and "blackmail," especially in developing nations. And he observed that "our government has no initiating program center, either for planning or for experimentation." In the draft report itself (*11*) he had written:

> A repercussion on the stability of the new countries and on the ability of the Free World to continue assisting them to a healthy development is a natural byproduct of any such large scale disruption of access to the world's basic raw material resources.

The first line of defense against these threats, Elliott continued, was the totality of U.S. defense and foreign policy programs, including foreign aid, support for U.S. allies, and regional alliances. The second line of defense was a vigorous program of technological development of substitute materials and conservation measures, supplemented by an adequate national stockpile. What was needed was a "balanced materials policy," designed and orchestrated at a high level of government.

Between 1963 and 1970, despite a growing commitment of U.S. forces in Vietnam, national materials policy received little official attention. Successive sales of "excess" materials were made from the national stockpile with formal legislative approval. The role of the Office of Emergency Planning diminished. Military attention was divided between maintenance of the strategic (nuclear) deterrent and an attempt to master with technology the adversary in Vietnam. Materials research and development concentrated on serving the "high technology" of aerospace, nuclear hardware, antiballistic systems, and military electronics.

However, in 1967, the Congress began to consider the subject of environmental quality. This trend involved a new approach to national materials policy. One concern was for the injury done to the land and the pollution of streams by strip mining. Another was for air pollution from fossil fuels, atomic reactors, metal refineries, aluminum reduction plants, and iron foundries. A third was the pollution of the land and air resulting from disposal of huge quantities of solid wastes. It became evident to more and more analysts that all forms of environmental pollution (except for such transients as thermal and noise pollution) were the consequence of the mismanagement of materials. Accordingly, environmental policy might have been perceived at the outset as one subset of national materials policy. As one study (*12*) pointed out,

> As a general principle, environmental degradation is the result of misplacing materials. Materials useful in one situation become harmful in another. Degradation of the environment can be halted by maintaining control over the location of materials. Application of this principle; however, becomes a complex problem, because materials vary in so many important respects: as to abundance, price, salvage value, useful applications and properties, ease of reprocessing, and injurious effects on the environment.

This study, prepared at the request of Senator J. C. Boggs (R–Del.), was followed in April 1969 by a report by an ad hoc committee, also organized at Boggs' request. The report called attention to the need for an adequate supply of industrial materials for peace or war, the need to practice frugality in the light of growing world demands for these materials, the need to satisfy ever-more-demanding requirements for improved properties of materials, and the need to manage materials so as to preserve a benign and unpolluted environment. To these purposes the committee proposed formation of a national commission to draft for congressional consideration a set of recommended policies governing the handling of materials from extraction to disposal (*13*).

Senator Boggs promptly introduced a bill to implement these recommendations. It was attached as an amendment (Title II—National Materials Policy) to the Resource Recovery Act of 1970, Public Law 91-512, approved 26 October 1970. The White House sent for Senate approval in June 1971 the nominations of the seven-member National Commission on Materials Policy (NCMP), they were accepted,

and the commission convened for its first meeting 15 September. The commission report recommended that we (i) provide adequate energy and materials supplies to satisfy not only the basic needs of nutrition, shelter, and health, but a dynamic economy, without indulgence in waste; (ii) rely on market forces as a prime determinant of the mix of imports and domestic production in the field of materials but at the same time decrease and prevent wherever necessary a dangerous or costly dependence on imports; (iii) accomplish the foregoing objectives while protecting or enhancing the environment in which we live; (iv) conserve our natural resources and environment by treating waste materials as resources and returning them either to use or, in a harmless condition, to the ecosystems; and (v) institute coordinated resource policy planning which recognizes the interrelationships among materials, energy, and the environment (*14*). The fifth point introduced for the first time in formal policy literature the concept of the interconnectedness of materials, energy, and environment, a relationship that was to become more salient as the energy crisis deepened.

Perhaps the most remarkable distinction between the Paley report of 1952 and the NCMP report of 1973 was that the former dealt extensively with the needs of national security but in the latter, military requirements were not touched on, and only passing reference was made to "security."

The Services Economy

The NCMP report was issued at a time when the United States was well into the third great epoch of economic change, the postindustrial or services economy. A graph depicts what was happening: Engineering materials and energy fuel consumption were roughly keeping pace with the population increase, but the gross national product (GNP), between 1940 and 1950, had begun a steep upward climb, with a second even steeper slope after about 1960. This GNP rise (in constant dollars) was attributed to the rapid expansion of employment and institutions producing services rather than goods. There were a number of implications for national materials policy to be derived from this development. For example, (i) the extractive and manufacturing sectors (producers and processors of materials) were a declining fraction of the total economy but no less essential to its total functioning; (ii) the tax base would be increasingly skewed because much of the services sector was tax-supported; (iii) hardware used by services industries (medical equipment, computers, aircraft, electronics, photocopiers, cable television, and others) tended to be "high technology" items characterized by high cost, frequent design change, and small volume, and requiring small quantities but a greatly expanded variety of essential materials with special properties; and (iv) the requirements of materials for the rapidly expanding services industries were superimposed on a continuing requirement for basic consumer goods that was keeping pace with the population growth. Taken together, these two sets of requirements presented a picture of tremendous complexity. It was increasingly difficult to know what was happening in materials markets.

Materials policy during the extractive epoch had been to discover, recover, process, and sell materials while improving the technology of their fabrication. During the manufacturing epoch, the policy had been to maintain sources of domestic and foreign supply, while further improving technology of use, materials performance, and conservation. Today, in the services epoch, the role of materials is vastly more complex, and the policy for their national management is correspondingly intricate.

For one example, the basic materials industries in the United States (such as steel, glass, and wood) increasingly tend to resist technological innovation. It is not for want of new inventions or technological ideas; high-risk innovations are seldom embraced in an established, highly competitive, narrow-profit-margin industry built large to exploit economies of scale. Many companies are faced with unmanageable capital replacement problems plus the costs of compliance with health, safety, and environmental regulations. Energy and natural gas shortages loom. Transportation presents uncertainties. Foreign competitors have newer capital equipment and often more compliant governments watching over them. American companies need a flexible stance, an ability to respond to challenges, exploit opportunities, and adapt to the new epoch. But they have grown rigid, even bureaucratic.

Another policy issue involves the relationship of materials to the dwindling U.S. resources of natural gas and petroleum and the prospective shortage of electric power. If the forces of the "free market" cannot compel energy conservation, the government may have to intervene. It is estimated that the U.S. steel industry wastes a third of the energy it buys. Steel technology in this country evolved at a time when energy was cheap; to convert to technology less wasteful of energy would exceed the industry's ability to raise the necessary capital. Similarly, the glass industry was built on the use of natural gas; it may not be able to afford today the costs of converting to electric furnaces.

A third policy issue relates to the heavy reliance of U.S. industry on imported materials. Virtually all U.S. supplies of chromium, manganese, cobalt, tin, columbium, aluminum, titanium, platinum, and palladium are imported. More than half of our fluorine, mercury, bismuth, nickel, selenium, zinc, tungsten, and cadmium comes from other countries. Other industrial countries are competing vigorously for supplies of these materials, and producing countries are exploring ways to exploit their monopoly position. Only the enormous agricultural strength of the United States prevents this country from suffering a persistent deficit in balance of payments. Among the options open are (i) a program of conservation to reduce the total amounts of materials needed, (ii) the building of commercial stockpiles, (iii) negotiation of a network of international agreements for the equitable sharing of world resources, (iv) vigorous research and development of substitutes either for use or as standby protection for the future. Some economists hold that market forces will operate effectively to correct shortages when they occur, but when industrial companies are already operating so close to the margin, the "correction" is likely to be achieved by their closing down.

Today national materials policy in a postindustrial epoch seems to require increased efficiency of use, reduced volume of throughput of materials in industry, increased recycling and reduced quantities of disposable wastes, reduced effluents, closer control over toxic and dangerous materials, more durable materials in engineering designs, and the development of systems of international cooperation in the sharing of materials and technology.

Developments Toward a National Materials Policy

There have been a number of important developments in the mid-1970's. For example, the U.S. Department of the Interior (notably from the Bureau of Mines and Geological Survey) has written a series of factual reports and policy studies in the field of minerals. There have also been stirrings in the Department of Defense and the Central Intelligence Agency. The General Services Administration currently has under way activities in materials planning, stockpile policy, long-range economic planning for industrial preparedness, and policy on priorities and allocations for De-

fense and the Energy Research and Development Agency.

A number of congressional committees are working on materials policy with support from the Office of Technology Assessment, the Congressional Research Service, and the General Accounting Office.

The report of the National Commission on Materials Policy to Congress inspired some 300 legislative proposals (*15*). Eleven committees have been exploring various aspects of materials policy in a post-industrial economy. Examples of the subjects under congressional scrutiny during 1975 include: solid waste management for energy conservation, resource recovery and recycling, stockpiling and stockpiled materials, import tariffs on raw materials, tax credits for material recycling, a permanent national commission, a materials forecasting agency, a materials and resources information system, economic stockpiling, utilization of existing stockpile for nondefense purposes, and materials science and technology and industrial health.

The Office of Technology Assessment (OTA) has under way a major program of assessments in national materials problems initiated under the direction of J. B. Wachtman, Jr., and continued by A. E. Paladino (*16*). The effort centers on three major programs, the adequacy of materials information systems for public policy-making, the accessibility of minerals on public lands, and the future uses of a national materials stockpile. These studies, all nearing completion, are being conducted under contract. Two other assessments address problems of recycling and materials aspects of product durability. Assessments in international trade and seabed mineral development will also have important implications for a national materials policy.

OTA's tentative plans for materials assessments center on such topics as the technologies of determining minerals in the ground and of offshore mining, materials limitations in energy systems, materials implications for new automobiles, R & D for recovery of metals from low-grade ores, and in substitutes for scarce materials.

The General Accounting Office has under way seven approved programs of studies concerning "industrial materials": (i) federal collection, analysis, and dissemination of raw materials' data, including forecasts of supply and demand; (ii) federal role as a proprietor of raw materials resources on public lands; (iii) international polices and practices and their impact on the availability of raw materials, including policies for controlling imports and exports of materials and agreements to develop seabed resources; (iv) federal research and development efforts to conserve raw materials, to increase supplies of materials, and to provide substitutes for the more rare and costly raw materials; (v) in-house policies and practices and contracting practices to conserve the use of scarce raw materials; (vi) federal organizational structure to cope with the interdependence of raw materials problem; and (vii) federal policies to stimulate the private sector to increase the production, recycling, and conservation of materials, through judicious land use, building codes, tax incentives, and so forth.

One congressional initiative is the Temporary National Commission on Supplies and Shortages (TNCSS). This initiative opened with a nationally televised address by Senator Mike Mansfield (D-Mont.), majority leader of the Senate, 1 February 1974, calling attention to the deteriorating condition of the United States in materials supply. A bill establishing the commission was introduced 22 May and passed and signed into law in September 1974. The commission was instructed to report its findings as to future prospects of shortages of materials and on the need for a permanent watchdog institution to foresee and to act in advance to meet future prospects of crisis relating to materials. The TNCSS, which held its first meeting 16 September 1975, 8 days after the appointment of the public members was announced, proposes to complete its report by 31 December 1976. D. B. Rice, president of the Rand Corporation, was designated chairman and George Eads, executive director (*17*).

On 19 November Rice and Eads met with Senator Mansfield who presented a letter cosigned by himself and Senator Hugh Scott (R-Pa.) urging the commission to implement the major recommendations of past studies rather than repeating them. What was needed, emphasized the letter, was "... *designing* the appropriate instrumentality that can provide strategic information assessments together with specific *policy options* that might be employed today to help mitigate or prevent the crisis, if any, perceived on down the road." The letter also referred to the need for a "coordinated strategic economic information system." The issue was not a free market economy versus a planned economy, but to provide a clearer perception of what lay ahead "so that the nation might better prepare itself." In other words, the commission should concentrate on designing an institution to collect and analyze information and define possible solutions for the problems it foresaw.

It is not yet clear whether the Mansfield-Scott letter will have its apparently intended effect of freeing the commission from the straitjacket of classical economic theory. The preference of conventional economists for a free market (or even the gold standard) neglects the painful consequences of market perturbations. It ignores the obvious departures from a free market occasioned by state trading, politically motivated boycotts, and competition with government-subsidized foreign purchasers for scarce supplies.

The Organization of Petroleum Exporting Countries has taught other developing countries several invaluable lessons. Freedom to drive two-and-one-half-ton automobiles at high speeds has been challenged. An envious world has looked on while we luxuriated in a high-consumption economy, but today the developing countries are realizing that the resources they possess are more potent as an economic weapon than is our threat not to buy them. National security requires a stable economy with assured supplies of materials for industry. In this sense, frugality and conservation of materials are essential to our national security. Security means more than safety from hostile attack; it includes the preservation of a system of civilization. We need to achieve the security of designing a way of life that is acceptable to us and compatible with the rest of the world.

The necessity for progress must be reconciled with the constraints imposed by the finiteness of materials, capital, and places to put our trash and pollutants. Good management includes getting maximum use out of each elemental atom, closing the materials cycle, maintaining the value of materials throughout the cycle, using the more abundant materials in preference to the less abundant, keeping the energy level of materials as high as possible, and using the smallest feasible quantity of materials to accomplish any given purpose.

Materials decisions are among the most widely diffused of all human activities. The consumer exerts his choice in the marketplace. The industrial design engineer, materials engineer, and process engineer make decisions about what goes into the product. The extraction and processing of materials into useful forms call for decisions from scores of industries. Prices of materials tend to fluctuate widely, according to the supply. The ideal is to have just enough all the time, with stable prices and orderly flows. Only in this way can rational decisions be made as to which material is most efficient in which application. On the other hand, when systems become this orderly, there is a tendency toward institutional hardening of the arteries. When this

happens, the system is ill equipped to respond to the changes that do occur.

I suggest three future policies in materials. First, we should identify those economic, technological, and political elements that encourage or discourage good materials management and respond to these findings. Second, we should maintain surveillance of all aspects of national materials management to detect emerging obstacles to good performance and lags in execution. Third, we should develop an institutional capability for (i) quickly correcting sudden deficiencies in national materials management and (ii) detecting and gradually correcting undesirable trends in the management of the materials cycle.

In more specific terms, these three policies translate into programs of action. Under the first we should make ground rules for the control of pollution the same everywhere, avoid springing sudden and severe restrictions on industry, encourage research to overcome observed defects in our use of materials or to expand opportunities for improved uses, establish standards to reduce needless variety of alloys or plastic compositions, and make the flows and price fluctuations of materials more regular. Most of the sensible measures in the management of materials are mutually supportive. For example, if we learn how to make our materials perform better with less, we can afford to pay more for them per unit, which means that we can afford to mine and process leaner ores; it also means that recycling is likely to be more profitable. Yet the price to the consumer of finished goods can remain the same.

With respect to the second policy, the main requirement is for better information about materials. Since the decisions on materials management are made in so many places, it is necessary that information appropriate to each kind of decision be made available where the decision is made. Adam Smith's theory was that all market transactions take place in the presence of complete information. We are far from this perfection in our management of materials; for the marketplace to function, we need to know more than we do now.

The Paley report of 1952 (*4*) best describes the program of action called for by the third policy: "There must be, somewhere, a mechanism for looking at the problem as a whole, for keeping track of changing situations and the interrelation of policies and programs. This task must be performed by a Federal Agency near the top of the administrative structure." The National Commission on Materials Policy also proposed that a "comprehensive Cabinet-level agency be established for materials, energy, and the environment" with a parallel organization in the Congress, and that as an interim measure a "Natural Resources Coordinating Committee" be established to "begin the task of integrating materials, energy, and environment policy." The Temporary National Commission on Supplies and Shortages now has the opportunity of closing this story that began more than a half-century ago.

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World Changes and Chances: Some New Perspectives for Materials

Trends in use, world trade, and international politics define issues and research directions.

S. Victor Radcliffe

In a controversial revival or reexamination of Malthus's hypothesis, system dynamics models of the world economy have suggested that the resource constraints of a finite planet will not permit ongoing trends in population and industrial growth to continue far into the future. Shortages of materials are identified as one of the key limiting factors. Despite their uncertainties, such analyses, combined with recent world events, do affirm the significance of materials and the other natural or physical resources as part of the larger economic and social system. It is in these terms rather than solely technical ones that this article focuses attention on the role of materials over the transition period from now into the early part of the next century and beyond.

How are we to get from here to there without being more certain where *there* is? How can goals and policies involving materials be formulated to facilitate the transition, and how can science and technology assist in discerning better the most likely long-term demands on natural resources—for what and in what quantities—and the options for meeting them? In particular, how can we better assess what priorities appear appropriate for materials research? This article attempts a preliminary attack on such questions. It is based on the belief that we must better understand the present and how we got here before we are likely to be prescient as to the resource needs and opportunities of the transition period and the further future.

Materials and Natural Resources

Appropriate research for materials, if it is to be conducted in the manner now accepted for such other major resources as energy and food, should encompass the full spectrum of activities involved in the materials system, that is, the resources from which materials are derived, their processing and utilization, and the discharges and wastes to which such activities give rise. The interrelationships of materials and the other natural resources are shown in Fig. 1 in terms of the flow of resources, as means to attain given ends, through the successive production stages of "raw materials" and "processed materials" (both of which figure prominently in world trade as the "primary commodities") into industrial use and consumer use. These different types of derived resources have key common features: (i) their importance lies less in their being specific things or substances than in providing "the function or operation of attaining a given end such as satisfying a want" (*1*), and (ii) they are dynamic, in that they are created, and in some cases, destroyed, by man.

The delineation of function as a key characteristic of materials is essential for understanding the forces that will determine what mix of resources, including both substitutions and new resources, will be called upon to meet national and world needs in the future. Correspondingly, it is not necessarily wise to extrapolate from the historical changes in the physical quantities and makeup of the resource consumption of industrialized countries in order to predict their future needs, except for the near term. It is even less likely that the needs of developing countries as they proceed to higher levels of industrial activity can be forecast from this same experience because their development is occurring in a different technological era.

The dynamic characteristic of derived resources arises from the fact that they originate as useless or neutral "stuff" existing on or in the earth and are transformed into useful substances through human knowledge. Thus, it is the creation of technologies to better meet human wants that has "created" such resources throughout industrial history. Examples of this process are the transformation (i) in the 1840's of the sap of a wild tropical tree into a resource for a new material, vulcanized rubber, for industrial and consumer products; (ii) of atmospheric nitrogen in the early 1900's into a resource for fertilizer for agriculture; and (iii) of uranium in the 1950's into nuclear fuel for electric power. Conversely, human activity can also "destroy" certain resources either directly or physically as in the use of fossil minerals for fuels and in the "working out" of individual metallic ore deposits, or indirectly through technological obsolescence, such as in advances that provide an alternative resource that is more economic than or that overcomes the physical limitations of an existing resource, or both. Indirect destruction of a specific resource by reduction of usefulness also may be complete in that the resource is returned once again to being neutral "stuff." The changing pattern of resources for rubber illustrates these types of "destruction." The original resource for natural rubber—wild trees in the Amazon forests—was abandoned after superior, specially bred, high-yield trees were cultivated on plantations in Malaysia. This change of the resource for a given material was followed in turn by the creation of an alternative material—synthetic rubber—to better perform the same functions, a development which resulted in the substantial replacement of natural rubber by a technically and economically competitive material that is derived from entirely different resources—oil and natural gas. Most recently, shifts in the relative costs of the above-mentioned fuel-mineral and plant raw materials favor some slowdown or reversal of this replacement trend.

One indicator of the relative significance of the different materials required in a modern economy is the physical amount of each in use. Such an analysis is shown in Table 1 in terms of pounds of the different materials produced annually for use in the United States. Although this indicator is crude in that it reflects only indirectly the functional value of the materials, there is yet no accepted way of making more direct comparisons analogous with the type of comparison used for energy materials that translates their mass into common units of energy measure or coal equivalent. Nevertheless, Table 1 does illustrate the important point that large proportions of

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both nonmetallic minerals and natural polymers (such as wood, rubber, plant fibers, wool, and leather) are included, in addition to metals, in the current materials mix required for an advanced economy.

While the bulk construction minerals in most countries are derived predominantly from domestic resources—usually close to the construction itself to reduce otherwise high transportation costs—the other materials are all major items of world trade. It is the varying degrees to which the different countries of the world depend on trade for the sources or markets for these materials for their continued economic development that, in large part, has raised a "materials problem" as the focus of so much international attention over the past several years. Depending on the country involved, the "problem" is not necessarily one of metallic minerals, even though such a mineral problem often is prominent. For many developing countries, the "problem" is one of natural products, and these substances also figure significantly in the materials "problem" in some industrialized countries.

Changes and Chances: Issues and Policies

What are some of the principal changes that have brought materials into prominence as issues of national policy and international relations? What opportunities are implicit in these changes? Both of these aspects of change and chance are apparent in three interrelated forms—physical, economic, and political. All three forms have been influenced by dramatic developments, especially since the 1930's, in the science and technology of materials (*2*). These advances have led not only to improved performance and lower cost for existing materials, but also to new materials with unique and precisely controllable properties that have created entire new industries, such as those of electronics and synthetic polymers, which, in turn, have contributed to economic growth and the demand for materials in general.

The first of these forms relates to the sheer magnitude to which physical requirements for materials have grown with increasing industrialization and economic growth across the world. As a consequence, it has been contended that continued growth carries with it implications for a level of materials demand which perhaps cannot be met, and for an accompanying effect on the environment that will be unacceptable if the level of discharges and wastes associated with present-day materials production and use is sustained. The statistics for current world production of materials illustrate the point of large scale impressively enough. However, implications as to the size of future needs are better understood by analyzing the changes in materials production over the history of economic growth for the most advanced countries, together with the likely influence of technological and social factors on determining and meeting future demand.

The nature of such changes for some major materials in the United States from the early 19th century to the present is illustrated in Fig. 2. The U.S. population has grown consistently over the entire period, and the gross national product (GNP), as measured in constant dollars over the period from 1870, likewise has grown, although generally at a higher rate than that of the population. However, the growth of materials has a different pattern. In the 1820's when the population had reached 10 million persons, the GNP was about $2 billion, and the principal metal production, in the form of pig iron, was about 60,000 short tons per year (1 short ton = .9 metric ton). By the end of the century, the population reached 76 million, the GNP approached $17 billion, and iron and steel production was about 15 million tons per year. Thus, with a sevenfold increase in population and a slightly greater increase in GNP, iron and steel production increased by a factor of 250. However, by 1950, when the population had doubled to 152 million and the GNP had risen even more rapidly, iron and steel production had increased only sixfold. In the subsequent period, the growth rate of iron and steel production was approximately that of the U.S. population. The curves for two other major metals, lead and copper, in Fig. 2 show similar indications of the tendency for materials production to grow more rapidly than population over a period of years and then to decline to a rate close to that for the population (*3*). The rapid growth period, which was some 80 years for iron and steel, lasted only some 40 years for copper and lead. Aluminum, which was not produced in significant quantities until more than 50 years later than lead and copper, is still in a period of rapid growth compared with that of population, although the period of highest growth rate appears to have been passed.

An even newer material—plastic or synthetic organic polymer—is likewise still in a stage of much higher growth rate than that for population. In contrast, the principal natural polymer in terms of tonnage use—wood—reached a maximum in its annual growth rate shortly after the turn of the century, and the rate has fallen since then to approximately that of the population growth. Nevertheless, over the entire period since the early 19th century, wood has had the largest production and use of all the materials other than the nonmetallic minerals (Table 1).

Wood provides a particularly good illustration of the apparent tendency of a material in a given economy to reach steady-state levels in per capita consumption rate with time. In addition, wood is an instructive example of the dangers inherent in trying to predict future consumption for a given material by extrapolation from its historical behavior without considering the principal functional applications and the factors that might give rise to new ones (Fig. 3). In 1900, when per capita total use (or use intensity) of wood was still rising, the principal applications were in the form of fuel (the larger part of the "other" category) and lumber for construction. Af-

Table 1. Use intensity of new supply of materials in the United States (in pounds of material per capita for 1972).

Material	Amount (pounds per capita)*
Nonrenewable resources	
Nonmetallic minerals	
Sand and gravel	9,000
Stone	8,500
Cement	800
Clays	600
Total	18,900
Metals	
Iron and steel	1,200
Aluminum	50
Copper	25
Lead	15
Zinc	15
Other metals	35
Total	1,340
Polymers (synthetics, mostly from oil and natural gas)	
Plastics and resins	100
Synthetic rubber	26
Noncellulosic fibers	22
Total	148
Renewable resources	
Wood and wood products (1971)	
Lumber	1,141
Plywood and veneer	224
Pulp product†	780
Other	77
Total	2,222
Natural rubber	8
Fibers	
Cotton	19
Other plant	1
Animal (wool, silk)	1
Synthetic (cellulosic)	8
Total	29
Leather	14
Grand total for all materials	22,661

*Data include imports (*32*). The use intensity of the new supply of energy materials (which are not included in the definition of materials used here) totaled 17,800 pounds per capita (1 pound = 0.5 kg) as follows: petroleum, 7800; natural gas, 5000; and coal, 5000. Likewise excluded are minerals used for the chemical and agricultural (fertilizers) industries, which total some 1650 pounds per capita. †Including paper.

ter 1910, these two applications declined in use intensity and absolutely. Over this same period, two newer applications—pulpwood (for paper products), and plywood and veneers—grew at rates much higher than that of the population. By 1940, their combined effect became sufficient to reverse the absolute decline in total wood use. Since then, the declining applications have been balanced by the increasing ones, with the result that the use intensity for wood as a whole appears to have become "saturated"—with corresponding implications for future demand for timber supplies, and for the intensity of environmental impacts resulting from wood production and use.

However, it is clear from Fig. 3 that this state of affairs is more apparent than real. What actually occurs to total wood use in the future will depend to a large extent on the character of the technological and social changes that develop outside the wood industry, as well as on the strength of the U.S. economy. An example is the rapid growth in the proportion of mobile homes in new housing construction over the past 25 years—homes that have tended to draw on a different mix of materials than the more traditional designs. Such changes demand functions that developments in wood technology can only attempt to provide more competitively than possible alternative materials. Some of these changes may be stimulated by the wood industry itself, as, for example, has been the case for chip board as a cheaper building material, but most are likely to arise elsewhere.

The above examination of use intensity for wood over a period of time supports the necessity for caution in extrapolating materials use intensities to forecast future consumption of specific materials. The forecasts for world consumption of major engineering and energy materials to the year 2000 prepared in 1972 for the U.S. National Commission on Materials Policy (*4*) are particularly open to question in this sense. The most detailed analyses concerning intensity of use draw on time series and cross-sectional information from different economies for examining relations among materials consumption, population, and GNP at different stages of economic development, and are coupled to micro- and macro-economic models for forecasting. Simpler variants of this approach applied to copper (*5, 6*), aluminum (*4*), and lead (*3*) indicate that, for aluminum and lead, the use intensity reaches saturation with increase in GNP per capita. However, for copper, there is disagreement as to whether saturation or a maximum occurs. The much more extensive analyses for steel (*7*), using a variety of modeling approaches, make it clear that, although the rate of growth of GNP is a key explanatory variable for steel consumption, several factors preclude accurate forecasting.

Thus, countries at the same stage of industrial development may have very different patterns of steel consumption, depending for example, on the presence or absence of a large steel user, such as shipbuilding. In addition, for the most advanced stages of development (in terms of GNP per capita), data are available only for the U.S. economy, and their utility is marred by disagreement among the models as to whether steel intensity is falling or constant at these higher levels of GNP. Likewise, the steel intensity behavior for Japan appears atypical. At present, it is apparent that theoretical understanding of the factors determining materials use intensities, even for relatively advanced countries, is at a very early stage of development.

Nonetheless, there are significant general indications of saturation in materials use levels as a function of disposable income. Likewise, evidence points to the importance of the technological character of the structure of a given economy in determining that level. The opportunities for a better grasp of the implications of further world economic growth for materials demand and the likely impacts that are offered by further improvements in this type of analysis are apparent. Of particular significance is the fact that, for the currently developing countries, the sequence of changes accompanying economic growth will not necessarily be the same as hitherto since the technologies used in their industries and infrastructures will have some opportunities to "leap frog" to the most modern forms. This is likely to occur even taking into account that appropriate technologies for many developing countries must be labor intensive if they are to contribute most effectively to raising economic well-being. The integration of use in-

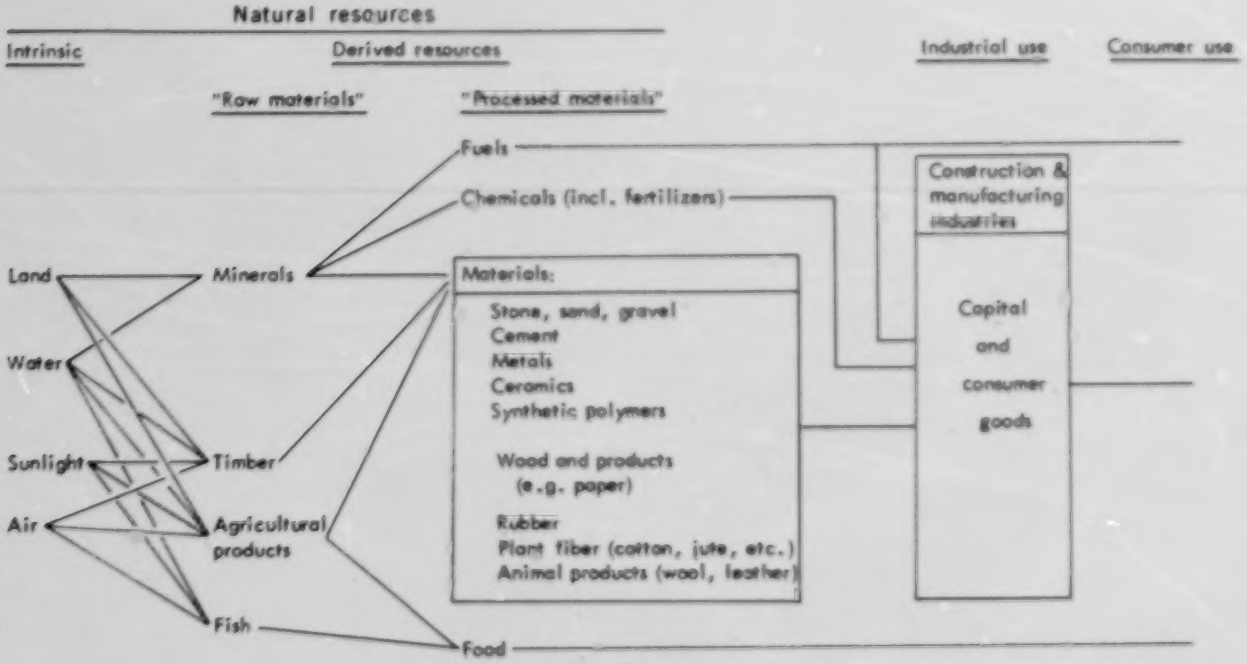

Fig. 1. Flow of resources through the production system.

tensity analysis with the type of demand-sector approach used earlier by Landsberg *et al.* (*8*) to examine likely resource requirements for the United States appears to be a potentially promising combination for examining requirements for the world.

The second and third aspects of change — the economic and political — are so interwoven that they are most usefully considered together. The significant developments here relate to the growth, in the period following World War II, of pressures in both developing countries and the industrialized nations for greater economic autonomy in the face of the realities of increasing economic interdependence. The effectiveness of the action of the Organization of Petroleum Exporting Countries (OPEC) in October 1973 in exercising control, for both economic and political purposes, of the supply and price of oil as a central element of the world economy marked a specific point of change in the relations between advanced and developing nations. The basis for that change and its consequences for the future are clearly much broader than the conditions under which oil (and other fuel minerals), food, and materials — the primary commodities — participate in world trade (*9*, *10*). Nevertheless, the proven world interdependence of the producing and consuming countries for such commodities points to opportunities as well as problems. The potential mutual benefits to resolution of the so-called North-South confrontations on materials issues over the past two years (*11*) are a practical case in point, in addition to the currently more pressing and important one of oil.

The main changes demanding the attention of materials producers and consumers alike are (i) the increasing dependence of many countries on imports of materials, (ii) the greater uncertainty of their prices, (iii) the rising interest of producer countries (whether developing or advanced) in domestic ownership and management, and in shifting toward exporting locally processed materials rather than raw materials, and (iv) the tendency on the part of some developing country producers and producer associations to try to use control of materials access and price as an instrument of advantage in international business and political negotiations (*12*). Examination of the makeup of world trade in materials and recent trends suggests some areas of leverage and mutual advantage.

The composition of world export trade (Table 2) for 1971 (the period just prior to the boom in commodity prices during the worldwide period of rapid economic expansion of 1972 and 1973) indicates that primary materials constitute about one-third of total world exports; the inclusion of processed metals in that category would not change the proportion dramatically. Except for fuels, exports from the advanced countries have the largest share for each commodity class; that is, some industrialized countries are major producers and exporters of materials and food, as well as being major consumers (Table 2). Correspondingly, the degree of dependence on developing countries for supplies varies widely. In the case of materials, the United States, for example, imported only 5 percent of its materials requirements in 1973 from developing countries, although some of those imports are considered relatively critical for reasons of security or economic health. The European countries and Japan are much more dependent on imported materials generally (for more than three-fourths of their consumption as compared with about 15 percent for the United States) and on developing country sources particularly.

However, while the share of developing countries in primary commodity trade is not dominant, except for oil and some critical metals, such trade *is* dominant in their sources of export earnings, even after discounting oil. Thus, there is a convergence of the interests of such exporting producer countries with those of importing consumer countries in that both groups stand to gain by expansion of materials production and export by the producers, the one expanding its industrial base and the other gaining a supply of materials needed for its existing industry. Despite this fact, the trends over the past two decades have been toward only a modest expansion of such exports from developing countries in terms of current dollar values and a decline relative to food and fuel exports (Table 3).

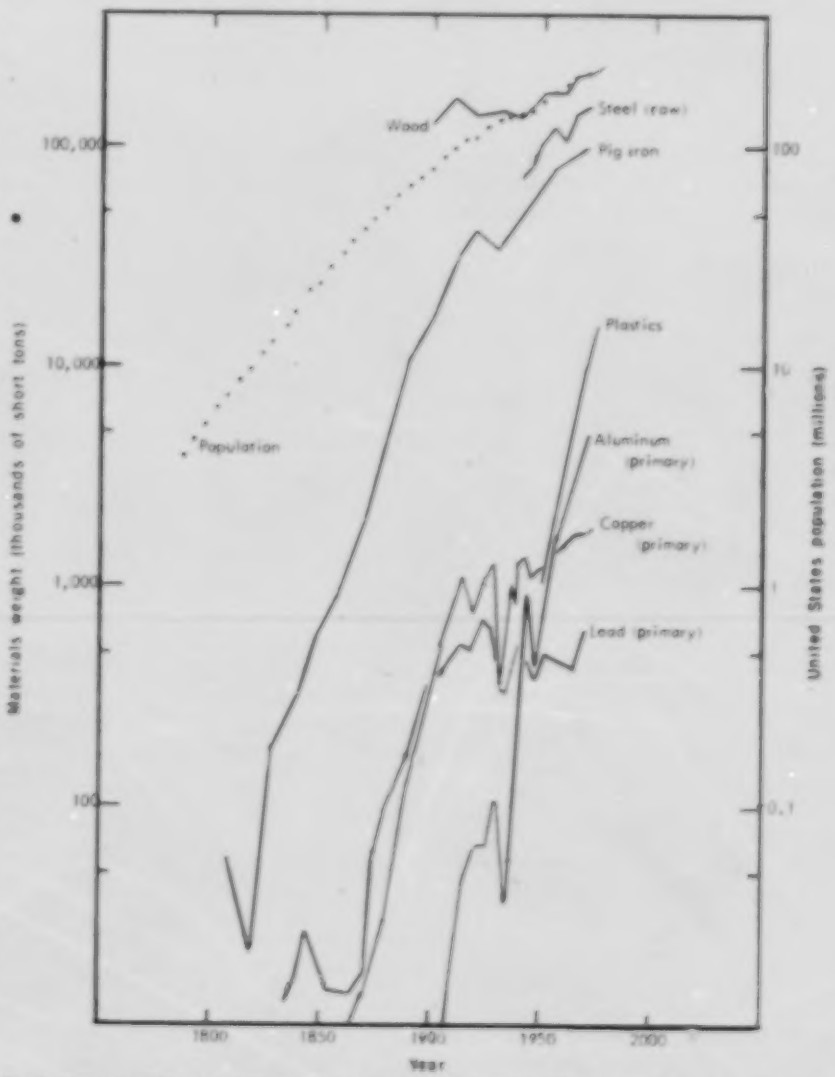

Fig. 2. Growth in the production of selected materials in the United States economy compared with the population growth since the early 19th century (*35*, *36*).

Furthermore, the data show the relative decline of nonfood agricultural materials (or natural polymers) from being twice the export value of minerals and metals in 1955 to being close to the same value in 1972.

For metals and minerals exports, which increased in absolute value almost three times over the period, the detailed statistics from which the data in this table were calculated show that the nonferrous group approached 60 percent of the export earnings from that sector, with copper minerals close to 60 percent of that amount. The aluminum mineral group increased in value fourfold over the period and shows a significant shift toward local processing. Thus, aluminum metal exports were 19 percent of the group value in 1972, up from essentially zero in 1955. Likewise, alumina (as opposed to bauxite) was up to 48 percent of the group value in 1972, compared with 18 percent in 1955.

The natural polymer sector, which includes the natural fibers, rubber, and wood, showed an increase of one-third in export value overall, but with absolute declines in jute, hard fibers, wood pulp, and rubber. The only strong increase was in wood, which increased by a factor of 3. (Correction of these various figures for inflation over the period would reduce the gains and increase the declines.) Over the past two decades, all these natural polymers have consistently lost markets to the synthetic polymers, which are derived largely from oil and natural gas and are manufactured almost entirely in the industrialized countries. With the exception of rubber and to some extent cotton, the intensity of research to improve the production, functional performance, and market competitiveness of the natural polymers has been minimal compared with the analogous efforts on the synthetics. Yet these nonfood agricultural products are strong elements of export earnings for a wide range of developing countries and are critical for some of the poorest. A good example of the latter is Bangladesh, which has derived as much as 85 percent of export earnings from a single natural product, jute. Thus, the further decline of the natural polymers in the export "basket" of the Third World countries could have significant effects on their rate of development over the next several decades, especially for those that lack or have been unable to develop mineral resources.

The preceding discussion points to the fact that, in practice, the major materials issues of the near- and medium-term future are concerned less with the "running out" of materials physically than with questions of their price and accessibility, and of shifts in the location of the materials industry (*13*). Thus, for 5 and 35 years into the future (that is, 1980 and 2010), the issues focus on continuity of economic activity and development in the industrialized countries, and stimulation of industrialization and economic growth in developing countries. While for many nations, the important issue of an adequate supply of strategic materials critical for military defense equipment must be addressed also, the character of contemporary defense strategies has, in principle, simplified resolution of that issue by use of stockpiles.

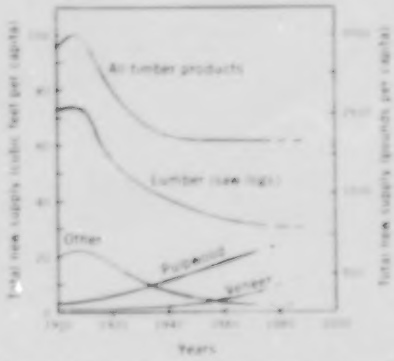

Fig. 3. Changes in the use intensities of wood and its principal functional applications in the United States economy since 1900 (*55, 57*).

The issue of price involves both stability and level. Excessive price fluctuations make export earnings and the availability of foreign investment capital uncertain for developing countries, tend to add to inflation (since price reductions in primary goods are seldom reflected by proportionate reductions in the price of manufactured goods), and stimulate substitution by consuming industries. Price levels partly determine profitability and, correspondingly, the ability to attract investment for further resource development. The upward pressures on costs from accommodating increased energy prices (and pollution control costs in the industrialized producer countries), from higher costs of capital equipment due to inflation, and from increased economic rents sought developing countries, to the extent that they are passed on, both raise prices of manufactured goods and encourage materials conservation and substitution. There are indications that such pressures may be reversing the downward trend, apparent from the early 1900's, in the relative costs of materials in industrial production shown by Barnett and Morse (*14*). The second issue, materials accessibility, subsumes their physical availability and addresses both consumer access to supply and producer access to markets. It involves variations in supply due to production undercapacity, producer restrictions or embargoes, export controls, and commodity market instabilities. Likewise, access to consumer markets varies with import controls, duties, and trade barriers on processed materials. Finally, the third of these major issues, that of industry shift, relates to the interest of developing countries in using indigenous materials resources to accelerate economic development through "value-added" industries that is, to export semifinished and finished materials rather than raw materials. Parallel to this interest is that of the world materials industries in locating production facilities so as to minimize overall costs of energy, pollution control, and transportation in the price of finished materials delivered to the major consumer markets.

Full recognition of the importance of these materials issues in international relations, and of the improbability of their resolution automatically by market operation or by such interventions as price indexing, has been relatively recent. Such recognition was included in the array of specific proposals for action put forward by the U.S. Secretary of State at the United Nations Seventh Special Session in October 1975. It is also emphasized by the inclusion of raw materials as one of four commissions (the others being energy, development, and finance) established at its initial working meeting in December 1975 by the Conference on International Economic Cooperation, as a forum for 27 nations representing the interests of industrial powers, oil-producing countries, and less fortunate developing countries.

The newness of such international activities emphasizes the present unreality of developing a world policy for materials; at best one can expect only guidelines and agreements on specific cases, especially in the face of the modest progress made up to now on the more pressing resource questions of food, energy, and environment. Nevertheless, there is much to be gained from efforts to develop a better framework for policy analysis relative to materials, rather than to continue to try to deal with specific questions in a compartmentalized manner. For minerals, both fuel and nonfuel, the concept of the "resource quadrilateral" frame of reference formalized by Connelly and Perlman (*15*) offers advantage in clarifying the different perceptions of the economic and political issues involving such energy and materials resources, together with the corresponding requirements from technology. The quadrilateral comprises four sets of countries grouped according to their relation to the major mineral resources—the "independent" exporters (Australia, Canada,

U.S.S.R., and the People's Republic of China), the less-developed country exporters, the industrialized-country importers, and the poor countries that are deficient in mineral resources. The translation of this type of conceptual framework into one for renewable and nonrenewable materials resources merits attention as a context for the analysis of materials issues.

Even for individual nations, the formulation of materials policies that are both comprehensive and operational is lacking. In a few developing countries that are rich in one or two specific mineral resources, the simple operational mode of maximum mineral exploitation in a manner to enhance economic development coincides with materials policy in this sense. However, as an advanced country rich in both minerals and timber, Canada is more illustrative of the present stage of materials policy development. There, the most relevant policy analysis is an ongoing study of minerals policy (*16*) (defined as policy for nonfuel minerals as sources of metals, nonmetallic materials, and chemicals) undertaken cooperatively by federal and provincial governments. It is oriented primarily to resource supply, in that it examines how best to use a particular class of raw material. As such, it can represent only a component of a materials policy for Canada. Nevertheless, the approach is innovative and of broad implication conceptually. The analysis identifies some 13 mineral policy objectives in the context of the three broader national goals of economic growth and development, sovereignty and unity, and quality of life. It suggests four options as the major policy directions possible for Canada:

1) Continue, as in the past, to encourage maximum mineral production.

2) Encourage economic diversification and growth through increased mineral processing and mineral-based manufacturing in Canada.

3) Obtain the highest possible net financial return to Canadians from minerals.

4) Conserve mineral resources for long-term domestic requirements.

The analysis defines as overriding concerns that minerals be managed to make best contribution to overall Canadian policies and priorities, and to ensure that Canadian mineral needs be met (either from foreign or domestic sources). It concludes that option 1 is no longer appropriate and ranks economic diversification as the highest priority objective, with increased financial returns from exports next. One immediate result of the analysis has been the enactment of federal legislation designed to achieve additional mineral processing in Canada.

While the Canadian study is intended to provide a basis for public discussion rather than a blueprint for action and is restricted to minerals, it exemplifies the type of larger public policy perspective desirable for the analysis of issues of national materials policy. Various recent studies have been directed toward examining country or regional policies for materials—as part of natural resources policy in Norway (*17*) and Sweden (*18*); as minerals policy in France (*19*); as raw materials policy (but specifically excluding food policy and energy policy) by the European Community (*20*); as part of commodity trade policy by the United Kingdom (*21*); and in the United States with respect to labor policy (*22*); to "materials" policy for minerals (including fuels) and renewable materials (*4*), and to critical imported raw materials (*23*). To varying degrees, all of these studies exhibit shortcomings in delineating clearly the overall policy issues for materials and the time scales over which these issues can be expected to be important. Correspondingly, they generally fail to offer priorities of objectives and actions, or a rationale for articulating a coherent policy for materials, as opposed to de facto existing policies or ad hoc developments that are common in all countries. Too frequently, such analyses give rise to questions as to whether the "problems" defined or the "solutions" offered are indeed the most appropriate on the basis of rigorous analysis of the context of the issues and the options available to respond to them.

Nonetheless, although the experiences of the past decade have shown how difficult it is to develop national policies for the other key resource areas of food, energy, and environmental quality, such policies are emerging to provide guidelines for both public and private sector activities in domestic and international affairs. A clearer understanding of the materials system in the sense in which we are now beginning to understand the other derived resource systems of energy and food, as well as their interrelations to one another and to the environment, is a prerequisite to a productive attack on addressing issues and options for materials policy.

Perspective for Materials Research

The above discussion has indicated a perspective for materials research that is new in emphasizing shifts in the priorities of government attention and public concern in some of the industrialized countries from the earlier role of science and technology in stimulating innovation through new and improved technologies and products. Materials research has been a key factor in that previous role, with innovative contributions in the form of materials having new or better properties to meet the stringent performance requirements of advanced technologies in the then high priority areas of defense, atomic energy, space exploration, and communications.

Table 2. Origin and composition of world exports, 1971 (*33*).

Commodity	Billions of U.S. dollars (f.o.b.)			
	Total world export	Advanced market economies	Centrally planned economies	Developing countries
Manufactured and processed products*	233.3	193.5	24.2	15.6
Primary commodities				
Food	50.4	30.8	4.7	14.9
Fuels	35.9	8.8	3.6	23.5
Materials	28.2	16.6	3.4	8.2
Nonfood agricultural	(18.4)	(11.2)	(2.2)	(5.0)
Ores and minerals	(9.8)	(5.4)	(1.2)	(3.2)
Totals	347.8	249.7	35.9	62.2

*Includes metals as distinct from ores.

Table 3. Developing country trade in primary commodities, 1955–1972: distribution of export shares between and within major classes (*34*).

Commodity	Relative dollar value (percent)				
	1955	1960	1965	1970	1972
Food	39.6	37.0	36.5	32.0	30.0
Fuels	27.3	30.8	35.3	39.8	46.9
Materials	33.1	32.2	28.2	28.2	23.1
Nonfood agricultural	(22.2)	(20.2)	(14.9)	(12.1)	(11.5)
Minerals and metals	(10.9)	(12.0)	(13.3)	(16.1)	(11.6)
	Dollar value (current dollars in millions f.o.b.)				
	21,911	24,798	32,035	45,480	57,640

In the advanced market economies, the thrust of publicly supported activities in science and technology over the past several decades has been directed to areas predominantly the responsibility of governments, or to other areas where contributions to national prestige or to the economy appeared promising, but where the relevant private interests were unable or unwilling to provide support (*24*). Recently, the importance of continued economic development in the advanced countries has been contrasted with the ineffectiveness in some of these countries of much private and publicly supported research for sectors of industry that are large factors in the economy and in employment; the situations in the United Kingdom (*25*) and the United States (*26*), for example, have been compared with the experience of Japan through the 1960's. Likewise, in developing countries, where investment in research has been necessarily more modest, analogous criticism is being directed to what is now construed as a previous overemphasis on basic science compared with the technological needs of such countries. Thus, in both industrialized and developing countries, there is currently a strong effort to better relate research emphasis to its potential and actual contribution to economic strength and development under the likely world conditions of the next several decades.

While the specific emphasis that is appropriate in materials research will vary in different countries, there are eight key categories through which science and technology can address issues of materials supply and demand (*27*). Increases in supply can be developed through: (i) advances in the understanding of mineral formation and the techniques for exploration, and of plant biochemistry; (ii) the creation of new materials or processes that open up new resources (for example, synthetic polymers, new mining techniques for minerals on land and in the oceans); (iii) improving the physical efficiency of the extraction of resources (for example, increased energy efficiency in processes for aluminum and steelmaking, or wood products); and (iv) developing lower cost alternatives for existing materials (that is, substitution of materials or systems to provide the same performance or function), including the possibilities for greater use of the more abundant materials, such as magnesium and silicon, or of renewable materials, including current organic wastes such as lignin. Likewise, opportunities for reducing demand for new supply lie in: (i) better integration of materials selection with component design to develop manufacturing processes that reduce materials loss during manufacturing; (ii) new or improved materials to permit engineering designs that reduce the amounts of material required to perform a given function (for example, miniaturization, as in solid-state devices, or improved reliability); (iii) conservation in use through improved materials performance that provides increased service life (for example, reduction in rates of deterioration by corrosion and wear); and (iv) improved recovery or direct reuse of materials during processing, manufacturing, and after completion of the useful life of capital or consumer goods.

Before these types of contributions can be effectively translated into specific research programs, a framework is needed in order to assess priorities of contributions and research. The study of materials science and engineering referred to earlier (*2*) identified for the first time the character of the total materials system in the larger economy as the basic reference frame against which to judge needs for materials research. At the same time, it clarified the complementary roles of materials research directed toward specific national goals or economic sectors—as for energy, health, or materials production—and of basic research that may have implications for several such sectors. Developments since then have been directed to improving quantitative understanding of the materials system, of its relation to broader domestic and international issues, and of the pattern of current emphasis in materials research in the advanced countries.

With respect to the latter, an initial analysis (*28*) of U.S. government-supported research and development defined the relative intensity of such effort across the materials system in terms of materials supply, utilization, and recovery; materials structure, properties, and performance; and materials-associated R & D on energy use in the materials system and with environmental effects resulting from its operations. More quantitative studies (*29*, *30*) have confirmed the strong differences in effort among these areas and questioned the adequacy of relevant policies as guides for materials research (*29*). Such questioning reflects the fact that the current overall program, in contrast with that for federal energy research, is simply the sum of efforts of different government agencies directed to different national concerns.

Whether the present spectrum is indeed the most appropriate one can be judged only against an analytical overview of national needs concerning materials, together with an evaluation of the significance and cost of research contributions compared with other ways of meeting those needs. Such questions of the points of maximum leverage for research within the materials system in relation to specific national objectives—for example, to minimize import requirements or energy costs—are being explored in a study involving economic and physical modeling through the Organisation for Economic Co-operation and Development (OECD).

In conclusion, it is suggested that there are three approaches by which materials research might address, for both industrialized and developing countries, the needs of the transition period and the future that lies beyond it. The first is in further examining the present system of materials extraction through recovery to improve its quantitative analysis and understanding as a basis for decisions on materials research in relation to given national or international concerns. The second is in assessing materials needs of the future with respect to the major technological and economic changes that appear most likely in the world economy (*31*). The corresponding constraints and opportunities, including questions as to the sociological factors determining materials consumption, have implications for the strategies for current research. Finally, there is the question of evaluating the effort necessary in basic research to assure provision of science-driven opportunities for future technological change. For all three of these approaches, the new perspective argued here for materials research relates them to the changing character of the interplay between government and industrial support for science and technology and the needs of economic and social development.

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Energy, Environment and Conservation

Energy Implications of Materials Processing

Earl T. Hayes

Energy, the capacity to do work, comes from a variety of fuels. Much of the work that society requires is the conversion of materials to a useful state. Without the energy from coal, oil, natural gas, nuclear power, and other sources, very few materials could be produced on the scale we are accustomed to. Thus, the broad-based, consumer-oriented industrial society that we now enjoy would be impossible.

During the 20 years from 1950 to 1970 the real cost of energy declined significantly; energy commanded $0.25 per million British thermal units (Btu's) (*1*) in the marketplace, and vast segments of society considered it as available as water from the tap. Increasing affluence, expectations, and population levels created tremendous demands for the cheapest, cleanest, and most convenient forms of energy; increases in fuel costs for environmental protection were discounted. Few believed warnings such as Hubbert's (*2*) that we would soon need to end such profligate consumption patterns.

Cook (*3*) estimates that human labor, at $3 per hour, costs $6000 per million Btu's; since human labor is the most expensive energy, industrialization can be defined as substituting fuel energy for human energy. Today society does not face the problem of running out of energy as much as it faces the task of changing its entire pattern of fuel consumption. This task is as difficult as any encountered since the industrial revolution began. Chemical engineers have traditionally performed materials and energy balances in their research. Such balances are needed today, as never before, because our accounting for energy consumption must go far beyond knowing that the steel industry consumes 5 percent of the nation's total energy supply or that to produce 1 pound of aluminum requires 6 to 8 kilowatt-hours of electricity in the smelting step. Today energy accounting, particularly in the materials world, must be precise and sophisticated.

Energy accounting, in the materials world, is an increasingly complex problem. The term materials is defined by Webster's as "the substance or substances from which things are or may be constructed." That definition, implying structural materials, has been broadened to include both fibers and fuel minerals; only food is still excluded. Thus, energy accounting must include metallic and industrial minerals, plastics, chemicals, and fuel minerals. The efforts of industry to extract these materials from nature and convert them to useful states requires more than one-fifth of the total U.S. energy budget.

General Approach

The definition of materials used in this article includes fuels as well as structural materials. Thus, in the analysis of amounts of energy required to produce usable substances, energy, materials, and dollars are exchangeable. Rigorous analyses of materials processing systems to determine unit energy requirements were not done systematically until the last few years. Such evaluations of metals, chemicals, and other commodities are just now coming into the scientific literature (*4–8*).

Each material requires its own analysis development under some broad guidelines. In one methodology, any specific materials analysis covering a commodity must be large enough to include the entire industry of any nation. All degrees of technological progress must be represented in the final output figures. Modern facilities must be taken together with outmoded plants and their energy efficiencies averaged. For example, zinc recovery systems vary in efficiency from 60 to 85 percent; all operating levels must be included.

Both upper and lower bounds limit energy analysis. The studies are constrained by the total gross energy figures of the United States. In the last 4 years this country consumed 69 to 73 quads (1 quad = 10^{15} Btu's) annually. The total energy used cannot exceed this figure. Data from the Bureau of Census (*9*) and the Bureau of Mines (*10*) provide more refined summaries of the total energy expended by specific industries; these values are upper limits for the particular industries. Lower limits include, for example, the energy used in the construction of a grinding mill or the calorific value of human labor. Such data are insignificant in overall energy studies dealing with tens of millions of Btu's per ton of material. The whole subject of energy subsidies in the form of research, processing plants, and true net energy are covered in the paper by Gilliland (*11*).

Society must know the energy requirements of all industrial materials for many purposes. The most important are for determining (i) the energy intensiveness of specific materials, (ii) the national requirements for specific materials industries, and (iii) energy flow diagrams paralleling process flow diagrams. These factors help guide the selection of materials. Further, they aid those seeking to conserve energy in present systems and to minimize energy requirements in developing new technologies.

Metallic Materials

Several studies have appeared in the last 3 years: most recently, the Battelle Columbus Laboratories performed a complete evaluation of energy in materials for the Bureau of Mines (*12*). Battelle employed basic metallurgical flow sheets, starting with ore in the ground and proceeding through the steps of mining, transportation, concentration, and reduction to the metallic ingot stage. They then assigned energy consumption rates to each step in the flow sheets. Census data, Bureau of Mines surveys of industrial consumption and production of energy, information on industrial operating experience from several sources, and other published information provided the basic energy data. In the Battelle study all energy inputs were converted to a common factor, British thermal units; a value of 10,500 Btu's (thermal) per kilowatt-hour was used for electricity.

Two metals, copper and iron, are of particular interest because of their significance to society. Copper is important because it is such a good conductor of electricity and heat; these properties are essential in an industrialized society. Iron and its alloys are the most versatile metallic materials available to man and are produced in the largest amounts. Without copper and iron the U.S. economy could not hope to meet the demands of the people.

A simplified flow sheet for processing 1 ton of copper from a sulfide ore containing 0.7 percent copper (near the current average grade) appears below. The energy con-

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← *Courtesy Stuart Finley, Falls Church, Virginia*

sumed in each step, expressed in millions of Btu's, appears in parentheses. The accuracy of the total energy was estimated to be ± 10 percent (*12*).

Mining (21.6)

↓

Concentration (42.3)

↓

Smelting (38.2)

↓

Refining (10.2)

↓

Refined copper (112.3)

Some copper is recovered by leaching heaps and waste dumps with sulfuric acid. The process precipitates the copper from solution, electrochemically, with ferrous scrap. A separate flow sheet developed for that segment of the industry shows the energy (10^6 Btu's) needed to produce 1 ton of cement copper.

Sulfuric acid solution
(largely self-generated)

↓

Pumps (4i)

↓

Waste dumps (0)

↓

Precipitation (45)
(2½ tons detinned steel cans)

↓

Cement copper (86)

Copper requires between 86 and 112 million Btu/ton. This high energy consumption stems from problems associated with the relatively low grade of the ore. Iron and steel require far less energy per ton of material produced.

The flow sheets developed for the production of steel slabs appear as follows, beginning with the traditional open-hearth furnace approach.

Blast furnace (17.4)

↓

Open-hearth furnace (6.1)

↓

Ingot casting (0.74)

↓

Slabbing mill (1.9)

Total: 26.1×10^6 Btu/ton

The basic oxygen furnace consumes slightly more energy because less scrap (and more hot pig iron) is used. The energy flow sheet shows 21.8×10^6 Btu/ton for the blast furnace and 2.8×10^6 Btu/ton for the basic oxygen refining operation, giving a total of 27.2×10^6 Btu/ton.

The third steel process, the electric furnace, uses a 100 percent scrap feed. The energy flow sheet appears as follows.

Scrap (0)

↓

Electric arc furnace (10.0)

↓

Ingot casting (0.74)

↓

Slabbing mill (1.9)

for a total of 12.6×10^6 Btu/ton. This low figure for steel from scrap represents a subsidy from the original blast furnace reduction. Note that in this case the iron is available for further recycling, whereas in cement copper the iron was consumed and therefore an energy charge. It is also a graphic demonstration of the importance of recycling.

The energy used by ten metal industries is summarized in Table 1. These ten metals accounted for 5.45 quads of the estimated total of 5.8 quads used by the primary metals industry in 1973, or almost 8 percent of the country's total energy consumption. A minor amount of energy was imported in the form of bauxite, iron pellets, chromite, and other raw materials. For purposes of uniformity, however, the study assumed that all materials processing occurs in the United States. Energy imports are offset by energy exports in the form of finished products.

An important factor to be considered is the energy expenditures associated with using plentiful domestic resources of lower-grade ores. Bravard *et al.* (*13*) calculated the added energy required for producing five metals from lower-grade ores. In the case of aluminum, lower-grade bauxite or clays would be favored over anorthosite for long-term development, the processing costs being nearly equal. The problems associated with processing lower-grade ores are due to the increased volume of material, which requires higher energy inputs for mining and transportation and a greater percentage of the total energy to be used in crushing and grinding. Kellogg (*14*) concluded that the most important element is the grade of ore. This is demonstrated in Table 2, taken from unit studies of the Battelle report.

The results given in Table 2 can only be considered indicative. For instance, 36 percent of uranium is mined underground, and the mining energy for that portion would be several times higher than the energy for surface mining. A straight-line projection of the figures for producing 1 ton of copper shows that for ore containing 0.18 percent copper, 628 tons of ore would have to be processed, 1840 tons of waste would have to be moved, and the energy for mining and concentrating would constitute 84 percent of the total process energy.

This is the same general trend shown by Kellogg (*14*) and Chapman (*5*) and is indicative of the rising energy costs of mining lower-grade nonferrous ores. It is only increased use of energy through mechanization that has made mining of such ores possible. Lovering (*15*) estimated that while U.S. mineral production rose 50 percent in the last 50 years, energy consumption went up 600 percent in the last 25 years.

There are three ways to counter this: (i) using better technology, such as a cheaper grinding process or in situ leaching; (ii) recycling, which uses 5 to 30 percent of the energy required to produce metals from ores; and (iii) making better use of the metals we produce — for example, doubling the life of an automobile.

Nonmetallic Materials

The nonmetallic sector consumed 1.9 percent of the total U.S. energy in 1973, and half of this was in portland cement production alone. Some of the largest users in this class are shown in Table 3.

As a class, nonmetallics are almost an order of magnitude lower in energy intensiveness per ton than metallic materials. This is because they are much more common in nature, and they are generally processed "as is" without reduction of oxides or silicates or breaking of chemical bonds. However, they are highly transportation sensitive. Truck transportation of sand and gravel, for an average of 20 miles, uses more energy nationally than the magnesium industry. Thus, materials can be energy intensive like titanium, with a high energy requirement per ton, or they can be low like cement, but the national aggregate is substantial.

Energy Costs of Fuels and Electricity

A national energy accountability system also requires knowledge about energy inputs to such industries as coal mining, petroleum refining, and natural gas transmission. Adding their processing costs to the thermal value of the fuels produces total energy costs. In its own right, the extraction, conversion, and transportation of energy is the most energy-consuming sector of the American industrial scene. More than 20 percent of the gross energy of fuels is consumed in bringing energy to the materials processor. In practice, as described in this article, it is necessary to start with gross energy in arriving at energy costs per unit of material and, in effect, assign all these energy losses to specific materials. The energy unit costs of petroleum, natural gas, coal, and electricity will only be covered in general terms.

Coal production involves relatively low extraction and transportation losses. Capital, materials, and equipment, estimated at 2 percent of the fuel value, would represent 500,000 Btu/ton. The Bureau of Mines estimates that in 1973 it required $31,300 \times 10^6$ Btu's to mine and prepare a

ton of coal for market. It is estimated that the transportation energy is 330,000 Btu/ton for a total of 861,000 Btu/ton delivered coal.

Petroleum is not such a simple case. Capital and equipment costs probably represent 2 percent of the fuel value. Lease and plant fuel value would add another 2 percent. Transportation by pipeline and tanker to a refinery also represents about 2 percent of the crude energy value. The refining operation itself uses tremendous amounts of petroleum fuels, natural gas, and electricity, which translate to more than 700,000 Btu's per barrel of crude oil. This amounts to 11 percent of the total energy to refineries, counting both crude oil and auxiliary fuels. On a national scale, it amounted to 2.83 quads in 1968 or 4.7 percent of the total energy of the United States. The petroleum industry consumes about 17 percent of its own energy equivalent in going from exploration to distribution of refined products.

In the United States 3 percent of all natural gas is used as transportation fuel for pumping the gas from well to consumer. Lease and plant fuel used in extraction probably account for 2 percent. Other energy costs represented by equipment and capital are also estimated at 2 percent, so that 93 percent of the fuel value is delivered.

The energy costs of bringing fossil fuels to market are shown in Table 4. In energy accountability this shrinkage is assigned to specific classifications such as extraction, petroleum refining, and transportation.

Electricity, a secondary energy form, is far and away the most expensive [as well as concentrated (*11*)] in terms of energy cost. Yet, it is the fastest-growing sector. Some two-thirds of the input energy of the fossil (as well as nuclear) fuel is dissipated either in its transmission to the user or up the smokestack and down the river in the cooling water. In 1971 the United States consumed 25 percent of its gross fuel inputs to produce electricity. It used a gross of 17.4 quads and lost the greater part of 11.9 quads in the production and transmission processes. Some small fraction of the waste heat was used. In discussions of energy per unit of output, the conversion of electrical energy has to take this loss into account. Theoretically, the conversion of 1 kilowatt-hour of electricity provides 3413 Btu's, but more than three times that much thermal energy is needed to generate and transmit that much electricity. A figure of 10,400 Btu's (thermal) based on actual industry measurement is generally used in this country. This figure has come down from a heat rate of 15,600 Btu's per kilowatt-hour in 1947.

In summary, the energy inputs of fuels for materials processing in the United States in 1971 were 12.56 quads for coal, 30.49 for petroleum, 22.73 for natural gas, 2.80 for hydroelectric power, and 0.41 for nuclear power—a total of 69 quads. Prorating electricity conversion losses and subtracting 5.7 percent for nonfuel uses (feedstocks, lubricating oils, and road materials) gives a net energy output of 57 quads.

Energy Costs of Plastics and Chemicals

More than 90 percent of the feedstock of fuel and petroleum products in the United States is used in a half-dozen chemical industries (*6*). Gross energy inputs can be measured, as well as energy contained in the primary products. Past this point, the distribution or determination of energy per unit of material becomes stickier. For in-

Table 1. Energy requirements for selected metals in the United States in 1973 (*12*).

Commodity	Product	Energy required	
		Per net ton product (10^6 Btu's)	Total (10^{12} Btu's)
Iron and steel	Steel slabs	24	3350
	Gray iron castings	34	366
	Carbon steel castings	42	54
Aluminum	Ingot	244	1170*
Zinc	Ingot	65	92
Lead	Ingot	27	23.9
Copper	Cement copper	87	14.9
	Refined copper	112	221
Chromium	High-carbon ferroalloy	61	15.8
	Low-carbon ferroalloy	129	19.5
Magnesium	Metal	358	42.0
Manganese	Ferromanganese	49.5	33.0
	Blast furnace	46	17
	Electric furnace	52	16
Titanium	Metal	408	8.2
Uranium	Uranium oxide		
	Acid circuit	776	2.1
	Alkaline circuit	1123	2.2
	Resin-in-pulp	795	2.3

*In practice, 40 percent of aluminum electrical energy in the United States is derived from hydroelectric plants. The figure 244 × 10^6 Btu/ton in the Battelle report is reduced to 204 × 10^6 Btu/ton in calculating total U.S. use of 1.17 quads.

Table 2. Energy expenditures in mining and concentrating selected metallic ores.

Commodity	Grade (%)	Tons ore per ton metal	Energy per ton product (10^6 Btu's)		Percentage of total product energy
			Mining	Concentration	
Iron	30	4	0.61*	2.0	11†
Zinc	10‡	12	5.3	5.2	7
Lead	10‡	12	4.3	4.5	30
Copper	0.7	157	21.6*†	42.3	57
Uranium	0.2	530	332.4*	246.6	58

*Surface mining. †Pellets. ‡Estimated.

Table 3. Energy requirements for selected nonmetallic materials for primary products in the United States in 1973.

Commodity	Product	Energy required	
		Per net ton product (10^6 Btu's)	Total (10^{12} Btu's)
Calcium	Quicklime	8.5	182
Cement	Portland cement	7.6	688
Ceramics	Common brick	3.5	62
Glass	Glass containers	17.4	216
Refractories	Basic brick	27	18.2
	Fireclay brick	4.2	6.9
Clays	Kaolin	2.8	14.3
Gypsum	Other clays	0.1–5.3	16.7
	Calcined gypsum	1.5	19
Sand and gravel	Sand and gravel	0.056	53
			1276.1

stance, ethylene accounts for not only its own feedstock requirements, but also those of ethylene oxide, ethylene glycol, and, in part, ethylbenzene and styrene. Also, ethylene produced from naphtha contains propylene, butadiene, benzene, toluene, fuel gas, and other by-products. It is beyond the scope of this article to trace out allocations of energy below the primary processing step.

The industrial use of energy for 37 selected chemicals in six standard industrial classifications (SIC's) in 1973 is shown in Table 5. The total represents 4.8 percent of all U.S. energy in that year. The six largest energy consumers in this group are shown in Table 6. Ethylene represents stored energy in that the creation of the double bond requires extra process energy. This energy can be released in later manufacturing operations involving ethylene dichloride or polyethylene. The triple bond in acetylene is also reflected in its high unit value.

The phenomenal growth of the plastics industry merits special attention (*16*). The process energy requirements range from 45×10^6 to 70×10^6 Btu/ton for polystyrene to 135×10^6 Btu/ton for low-density polyethylene. The plastics produced in the United States in 1973, estimated at 14×10^6 tons, required 1.4 quads of process energy, making plastics a larger consumer than the aluminum industry. The stored energy in the finished plastic is roughly equivalent to the hydrocarbon input and requires a raw material input of 0.6 to 0.8 quad. The only way to recover this energy is by combustion. This demonstrates that the plastics industry is one of the largest users of materials processing energy. However, unlike scrap metal, the material discarded by consumers can only be recycled as a fuel because of the present limitations of resource recovery technology.

Implications

Processing of many materials could become energy-limited rather than resource-limited. The methods required to provide metals, industrial minerals, and energy fuels and materials in useful forms all consume significant quantities of coal, oil, gas, and electricity. The materials industries use more than 20 percent of the nation's energy in processing metals (8 percent), chemicals and allied products (7.8 percent), petroleum refining (4 percent), and nonmetallics (2 percent). Steel, aluminum, plastics, cement, and gasoline account for half of this. The issue becomes complex when one considers that each material has its own level of energy intensiveness and that there are many ways in which energy can be lost or saved in the total economic system. Despite those problems, certain broad implications emerge for metallic, nonmetallic, and energy materials.

The data available for metallic minerals are the best defined. Further, the significance of metallics in the economy carries a clear requirement that energy intensity be considered in planning for their extraction and usage. Within that context, it becomes tempting to oversimplify the problem. For example, some 25×10^6 Btu's are needed to produce a ton of steel and 245×10^6 Btu's to produce a ton of aluminum. Thus, energy accounting might appear to mandate use of steel in preference to aluminum. But a ton of steel occupies one-third the volume of a ton of aluminum, so that substituting aluminum would greatly lower the energy savings per volume of material used. Further, for goods that are transported or used in transportation, lighter-weight materials provide additional energy savings. The same reasoning applies to plastics. Thus, energy accounting cannot provide as simple an answer as might be assumed from the initial data.

One clear planning precept does emerge, however. Each material has a fixed lower bound of ore grade, below which energy costs make processing uneconomic. As noted above in the case of copper, the energy costs rise rapidly as ore grade decreases. At some lower limit, say 0.25 percent, the energy expenditures dominate the whole recovery picture. Technological improvements in rock disintegration, transportation, and concentration will have to be made if such low-grade ores are to be considered reserves—that is, resources that can be processed economically.

In the case of energy materials, both extraction and refining have serious energy implications for the economy. As extraction becomes more difficult and more refining takes place, more energy is lost. For example, two-thirds as much oil as has ever been found is still in the pores of the host rock. One of nature's contributions to oil extraction has been the pressure of the accompanying natural gas, which forces petroleum through pores to collection centers of drilled wells. Most secondary methods of recovery involve pumping of various chemicals and fluids to force out the oil. The pumping energy alone places finite limits on the amount of total petroleum eventually recovered from different reservoirs. Also, more energy is used today in the search for oil—40 years ago 275 barrels of oil were found per foot of hole drilled; the comparable figure today is on the order of 25 barrels.

The refining of petroleum presents one example of energy losses incurred in making a fuel more useful. Conversion of solid coal into more useful products by gasification or liquefaction presents another example. About 10 to 20 percent of coal energy is expended in making a low-Btu gas (170 Btu's per cubic foot) and another 15 to 25 percent is used in upgrading it to pipeline-quality gas (1000 Btu's per cubic foot). Electricity, the most ubiquitous and concentrated energy form, offers the ultimate example of energy losses incurred in a refining process.

Table 4. Energy costs of bringing fossil fuels to market.

Commodity	Energy used	
	Percent	Btu's per 10^6 Btu's
Coal	3	30,000
Petroleum	6	60,000
Petroleum refining	11	110,000
Natural gas	7	70,000

Table 5. Energy requirements of six SIC groups in 1973. Numbers in parentheses identify SIC groups.

Industry	Energy (10^{12} Btu's)		
	Process	Feedstock	Total
Alkalies and chlorine (2812)	475.8	0	475.8
Industrial gases (2813)	110.5	48.9	159.4
Inorganic pigments (2816)	35.1	0	35.1
Industrial inorganics (2819)	442.5	345.6	788.1
Cyclic intermediates (2815)	70.1	158.7	228.8
Industrial organics (2818)	556.9	1273.5	1830.4
Total (281)	1690.9	1826.7	3517.6

Table 6. Six largest users of energy in SIC group 281 in 1973. Only feedstocks not accounted for by one of the other selected chemicals are included. For example, benzene is charged against styrene while ethylene is not.

Chemical	Tonnage (10^9 pounds)	Energy consumption (10^{12} Btu's)		
		Process	Feedstock	Total
Ethylene (2818)	33.4	382.3	1078.0	1460.3
Ammonia (2819)	30.3	271.7	345.6	617.3
Chlorine (2812)	19.2	398.6	0	398.6
Styrene (2815)	6.0	51.1	86.6	137.7
Methanol (2818)	7.04	34.3	91.7	126.0
Acetylene (2813)	0.58	8.27	38.8	47.1

The interweaving of energy losses in metallic and energy mineral processing can be dealt with, but only through a total systems analysis. Chapman (*5*) cited data on smelting copper by thermal-fired compared to electrical-heating sources. At first glance, electricity is favored 2 to 1 on the basis of heat input, but when heat rate is factored in the ratio is almost 2 to 1 against electricity. The moral of this example is best expressed in Chapman's words. "It is a disturbing conclusion that in good faith an industry could improve its own thermal efficiency whilst increasing the national energy consumption."

It is that total systems analysis, of true energy costs and possible real energy savings, which is required if industry is to meet society's demand for materials in a world where energy, in all forms, is becoming increasingly expensive.

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Tensions Between Materials and Environmental Quality

Environmental regulations will constrain the availability and increase the cost of materials.

Richard A. Carpenter

Concerns about environmental quality interact in a complex way, depending on supply and demand of materials, to change usage patterns, availability, and costs. The energy and materials conversion systems of industrial society are closely linked to natural systems of photosynthesis and biogeochemical cycles. The National Commission on Materials Policy (*1*, p. 6-1) concluded that:

> The material resources and environmental quality of the Nation are affected by a lack of consideration of the two as a unit. Depletion of reserves and pollution have the same cause—failure to manage the flow of materials as a cycle, resulting in a resource depleting dispersal of energy and materials into the environment as pollutants. A national policy for the management of energy and materials is needed to transform this open-ended process of wastage into a substantially closed system.

This relation is well recognized but very difficult to deal with. Thus, considerations of major parts of the whole, such as this special issue on materials, are practical devices for analysis and planning only as long as the total context is not forgotten.

Environmental quality is a relatively recent gathering point for a variety of measures—both quantifiable and subjective—of importance to the management of natural resources. The National Environmental Policy Act of 1969 sought to place the full fair weight of environmental values on the scales of the decision-making process. The Congress declared a national policy "to create and maintain conditions under which man and nature can exist in productive harmony . . ." (*2*). The National Materials Policy Act of 1970 sought to "enhance environmental quality" and to develop a policy "to anticipate the future materials requirements of the Nation and the world . . ." (*3*).

The mixture of objectives within and between these two recent legislative expressions of national policy shows the development of thought about natural resources management. Neither exploitation nor preservation is dominant as a concept; a continually refined balancing among many goals is what is called for. Rather than making simple decisions whether or not to proceed with individual projects, the manager of natural resources is challenged to generate imaginative alternatives taken from as comprehensive a view as is reasonable. Trade-offs are to be made explicitly and in a process open to the public. The marketplace, with its time limitations and imperfect information about environmental impacts, has been augmented (or perhaps supplanted) by a growing array of assessment procedures and regulations. In fact, the single greatest source of tension between availability of materials and environmental quality may well be the increased difficulty and time lag involved in reaching acceptable decisions.

The desirability of balancing competing and often conflicting objectives in the use of natural resources leads directly to a second major problem: the dearth of complete, accurate, and timely information. Cause and effect relationships in ecosystems are not well understood because of the complexity of organisms and their environments. Ecology is not a predictive sci-

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ence in the sense of chemistry or physics. As for materials, far too little is known about their reserves, substitutability, and need as opposed to the demand for them.

The economic and social consequences of manipulating the cost and availability of materials to achieve some environmental quality or conservation goal are uncertain. Opinion polls record sustained support for control of environmental pollutions and a recent report by the Harris organization says 77 percent of Americans polled "would prefer a more modest life style over continued inflation, shortages, and repeated recessions" (*4*). However, this may not represent the view of the poor and disadvantaged who still aspire to greater material well being.

As a consequence of the lack of information, the codification of public concerns about environment and materials has resulted in elaborate administrative procedures for examination and use of a generally sparse data base. The following list comprises some of the current laws applicable to environment and materials questions:

National Environmental Policy Act of 1969 [42 U.S. Code 4321 (1969)]

Federal Water Pollution Control Act Amendments of 1972 [33 U.S. Code 1251 (1972)]

Marine Protection, Research, and Sanctuaries Act of 1972 [33 U.S. Code 1401 (1972)]

Clean Air Act Amendments of 1970 [42 U.S. Code 1857 (1970)]

Solid Waste Disposal Act of 1965 [42 U.S. Code 3251 (1965)]

Mineral Lands Leasing Act of 1920 [30 U.S. Code 185 (1920)]

Mining and Minerals Policy Act of 1970 [30 U.S. Code 21a (1970)]

Occupational Safety and Health Act of 1970 [29 U.S. Code 651 (1970)]

Coal Mine Health and Safety Act of 1959 [30 U.S. Code 801 (1959)]

Multiple-Use Sustained-Yield Act of 1960 [16 U.S. Code 528 (1960)]

Wilderness Act of 1964 [16 U.S. Code 1131 (1964)]

National Park Service Act of 1916 [16 U.S. Code 1 (19)]

Federal Food, Drug, and Cosmetic Act of 1938 [21 U.S. Code 301 (1938)]

Federal Environmental Pesticide Control Act of 1972 [7 U.S. Code 135 (1972)]

Federal Highway Act of 1966 [23 U.S. Code 138 (1966)]

Federal Power Act of 1920 [16 U.S. Code 800 (1920)]

Land and Water Conservation Fund Act of 1944 [16 U.S. Code 460 (1944)]

Oil Pollution Act of 1961 [33 U.S. Code 1001 (1961)]

Endangered Species Conservation Act of 1969 [16 U.S. Code 668 (1969)]

Taylor Grazing Act of 1934 [43 U.S. Code 315 (1934)]

Fish and Wildlife Coordination Act of 1958 [16 U.S. Code 661 (1958)]

Wild and Scenic Rivers Act of 1988 [16 U.S. Code 1271 (1968)]

Outer Continental Shelf Lands Act of 1953 [43 U.S. Code 1331 (1953)]

My discussion is drawn largely from recent advisory reports by the National Research Council, which assess the technical basis for making trade-offs in the energy, materials, and environmental system. These reports agree that tensions between materials availability and environmental quality will increase in the immediate future (*5*, p. 2).

> Given the present level of technology and what may reasonably be expected to evolve over the next decades, and given the prevailing view that materials consumption is the way to a better life, the facts indicate (1) materials throughput will double, and then double again, over the next thirty or forty years, (2) the quality of ores and other natural resources will decline and readily available sources be exhausted, (3) only by increased use of energy per unit of output and per capita will the intensity of materials throughput be maintained, and (4) the environmental stress per unit of production will increase correspondingly.

Pollution Control Regulations

Federal, state, and local regulations on the discharge of pollutants into the air or water have reached a stage of enforcement such that profound changes are taking place in manufacturing and processing industries. The gross and obvious pollution problems (for example, particulate matter in air and oxygen-demanding organic wastes in water) are being alleviated without much argument. Current regulations prohibit many materials processing practices of the past, such as those that led to sulfur dioxide damage from smelters in Tennessee and Ontario, hydrogen fluoride from phosphate plants and aluminum smelters, and heavy biological oxygen demand loadings from pulp and paper industries.

These clean-up efforts require relatively large amounts of capital that in some instances is being diverted from the plant construction and improvement that would otherwise be devoted to supplying additional materials. Power plants, cement plants, paper mills, ore processing operations, steel mills, and petrochemical installations are among those affected by large capital costs for pollution abatement, outlays which usually yield no return on investment although they are justified in the national interest. The availability of otherwise usable materials is thus constrained (*1*, p. 6-14).

Another demand on capital is for research, development, and innovation in the basic materials industries. A recent report of the National Materials Advisory Board gives the results of a survey of forest products, glass, steel, and plastics industries. In each the ability to attract capital for technological improvements has been adversely affected by government regulations on price, profit, safety, and environmental correction (*6*).

The staff draft report of the National Commission on Water Quality (*7*) estimates the capital costs for achieving the pollution control mandated by the Federal Water Pollution Control Act Amendments of 1972. Table 1 is adapted from that report to show data of interest to the materials industries.

As emission restrictions for new plants become progressively more stringent, changes in processes and products become less costly than discharge treatment in achieving environmental protection. These design revisions are altering raw material requirements and by-products.

The use of materials for pollution abatement may affect their supply for other uses. For example, by-product lime from the calcium carbide process is insufficient to meet the demand for sulfur oxide scrubbers in electric power plants and smelters. The use of noble metal catalysts in controlling automobile exhaust may have the eventual effect of concentrating platinum and palladium (in the used converters) for recovery and reuse.

Pollution control through the elimination of wastes can also be a new source of materials. It is probable that the sulfur in coal will be recovered in elemental form or as sulfuric acid as new scrubbing technology develops. The use of fly ash has been the subject of considerable research, and this recovered waste may be a future source of some metals. Sludge from sewage treatment plants and food processing is being applied to agricultural land as a method of disposal with some benefits to plants from nutrients contained in the sludge. Phosphates may also be recovered from such sludge.

Many hazards to human health are now identified as contaminants in the environment. Of course, these substances usually have an adverse effect on natural ecosystems also. Leakages from the materials cycle will be subject to increasing regulation and control which will add substantially to costs of processing and manufacturing. Examples include asbestos wastes, cadmium, mercury, arsenic, and other metals, halogenated organic compounds, and particulate sulfate aerosols.

Multiple Uses of Land

The mining of raw materials, particularly at open-pit or strip mines, is encountering competition from other uses of the surface and desire for its preservation in terms of environmental quality. The purpose of state and proposed federal laws is to pre-

vent exploitation of deposits unless the land surface can be rehabilitated and the productivity of the existing ecosystem reestablished. Aversion or repair of damage are often technically feasible at reasonable cost (*8*). However, in the arid West, the conditions for satisfactory restoration of a landscape may be so uncertain that mining is not permitted.

Other mineral resources may underlie a unique natural phenomenon or an area of such great environmental value that surface disruption, even if rehabilitation were plausible, would not be allowed. The supply of natural amenities is diminishing relative to the demand for them. This is due to a number of factors, including a growing population, affluence, and an appreciation of parks, recreation areas, and wilderness. On public lands, the very access necessary for exploration (roads, test drilling) may be limited by environmental regulations. Estimates of the practical possibilities of extracting lower grade ores where the extent of surface disruption would be widespread should be tempered by the recognition that these areas may be preempted because of their environmental value.

As abatement of point source pollution (for example, discharge of waste by a single factory) is achieved, the further improvement of water quality to meet the criteria for water contact recreation and the propagation of fish may require attention to nonpoint sources such as agricultural runoff and mine drainage. Drainage from mines, whether acidic or not, affects the quality of surface and ground waters. New underground mines may have to be engineered to minimize interference with natural aquifers and degradation of water quality. Surface subsidence is a long-term disturbance of the landscape which will be assessed as a part of the decision to proceed with new mines.

Mine wastes, mill tailings, slimes, and muds must be handled to minimize off-site effects. Underground stowage of wastes in the mine itself and stabilization of surface deposits may be required.

Materials from the outer continental shelf and the continental slope will not be recovered unless the marine environment is protected. The environmental impact assessments now under way in the leasing of oil and gas reserves and the extensive collection of marine ecosystem data sponsored by the Bureau of Land Management are the beginnings of the necessary understanding of risks to the environment from undersea technologies. A recent report (*9*) considers that there are commercial mining possibilities in the near future for sand and gravel, metal sulfides, phosphorite, heavy mineral sands, and shells on the outer continental shelf, as well as for ferromanganese nodules in the deep ocean. The environmental impacts on shore from transporting and processing these materials will be as important to plan for as those in the ocean.

Table 1. Estimates of capital costs for water pollution abatement.

Industry	Capital costs to achieve limitations (in millions of dollars)		Abatement capital expenditures as a percent of total investment in each industry 1975–1983
	1977	1983 costs in addition to 1977 costs	
Mining	3,040	0	15.2
Iron and steel	2,910	949	9.0
Pulp and paper	2,640	798	11.5
Textiles	537	300	8.3
Chemicals	4,970	4,173	16.6
Nonferrous metals	75	120	1.5
Stone, glass, and clay	75	66	1.5
Lumber	14	25	0.3
Rubber	220	48	2.0

The same report (*9*) finds that "industry must be willing to disclose data on the technology of mining pertaining to those elements of mining systems that directly intersect with the environment." Thus, some means must be devised of protecting proprietary information while adequately regulating for environmental protection. The early stage of development of ocean mining presents industry with "an opportunity to design hardware and operating methods that will minimize potential adverse environmental consequences."

The regulation of mining on the outer continental shelf will proceed from the prelease environmental impact statements required by the National Environmental Policy Act. In the international region of the deep ocean, the situation is less certain, although the federal government will probably require U.S. firms to conform to the same environmental protection regulations that would apply domestically.

The sites of large installations for processing materials or for waste disposal will be dictated by changing regulations of land use. The National Commission on Materials Policy (*1*, p. 7-1) concluded that:

> Competition for land is intensifying. Urban expansion, highways, airports, reservoirs, recreational subdivisions, etc., take up approximately 1.2 million acres every year. Commercial forest land declined 1.7 percent between 1962 and 1970. Surface mining, which produces 50 percent of our coal and 90 percent of all other minerals, is under attack. Materials production is prohibited or severely restricted on over 100 million acres of Federal land. Large additional areas are being proposed for restrictive withdrawals.
>
> Valuable deposits of sand, stone, gravel, and clay are being covered up by urban growth or zoned out of effective use. Similar impacts limit sites for recycling plants and waste disposal. Strong objections are being registered on environmental grounds against proposed new power plants, transmission lines, refineries, offshore oil drilling, deepwater ports, and other processing and transport facilities.

The enforcement of uniform standards for ambient air and water quality throughout the nation is being challenged on the basis that the natural capacity to assimilate some wastes is an economic benefit that should not be foregone arbitrarily. The concept of nondegradation of air quality might prohibit new plant construction in the locations most desirable in terms of raw materials. Variations in landscape characteristics and meteorology suggest flexibility in setting environmental goals. In some areas, materials processing industries will be limited in growth by the capacity of the landscape to accept wastes. In many large cities, if water quality standards are to be met, the disposal of wastes to water will be limited even if all practical sewage treatment is implemented. These uses of, and limits to, the assimilative capacity of the environment will add a new dimension to calculations regarding plant sites.

Conservation and Waste Management

Another recent report (*10*) states that:

> Environmental costs of materials supply, already severe, will increase still further in the absence of firm and continuing precautions, and perhaps even with them. To produce, fabricate, and dispose of wastes from ever larger quantities of metals obtained from ever leaner deposits demands ever larger investments of energy and creates growing potential for damage to all aspects of our environment on, above, and below the land surface, including living organisms. Conservational measures are needed, not only to stretch our resources but to restore, protect, and perpetuate a livable human habitat.

Environmental concerns have become important in determining the use of materials. Frequently, a coincidence occurs between the desire for resource conservation and environmental quality objectives. For example, lead is a relatively scarce metal,

and its dispersion as tetraethyl lead in gasoline precludes recycling it. Now, lead additives in motor fuel are being eliminated because they poison the emissions control catalyst and are probably a risk to human health in urban areas. Aluminum from bauxite is also potentially limited in supply and requires a large amount of energy for its production. A concerted effort to recycle aluminum containers is being stimulated in the interests of reducing litter. Phosphates are an essential plant nutrient and are dispersed in agricultural practice. Their use in detergents has been decreased because of evidence that lakes receiving municipal sewage become eutrophic and deteriorate under algae growth. In such cases, conservation and environmental quality are both served.

The Committee on Mineral Resources and the Environment (*11*) concluded that:

> Efficient recycling of materials from industrial and municipal waste has become recognized as a major opportunity for conservation of materials, energy, and the environment. The greater the number of product-cycles materials can be put through the less the demand on prime resources. It is helpful to think of industrial and municipal wastes as a novel form of ore but one which is quite widely dispersed and therefore lean, especially the municipal wastes.

Recycling, unfortunately, can sometimes lead to the contamination of virgin materials. Polychlorinated biphenyls (PCB's) were, until recently, used in plasticizers and "carbonless" carbon paper that ended up in paper wastes. These chemicals are toxic to humans and other organisms and are concentrated in some fish by up to 500,000 times the amount in the ambient water. The Food and Drug Administration has set PCB tolerances for food packaging materials and various foods; the Environmental Protection Agency will probably soon set effluent standards for PCB's. Paper processing plants are finding their stock contaminated and their effluents suspect due to incorporation of PCB's from recycled paper. A materials conservation policy has backfired.

Energy, its production, conversion, and use, is the direct cause of much environmental damage (for example, recovery of fossil fuels, waste heat rejection, and combustion emissions). Regulation of these environmental consequences of energy use will have some effect on its cost and supply. As energy becomes more expensive, patterns of using it will change for those materials that require large energy inputs. Energy efficiency considerations will change processing and manufacturing technologies. For example, fuel costs will act to decrease the weight of automobiles, thus changing the quantity and type of materials in them and subsequently decreasing total automobile emissions. In this interconnected system of energy, materials, and environment, a reduction in the consumption of energy most often will conserve materials and improve environmental quality.

Renewable resources for materials (that is, the photosynthesized products of forestry and agriculture) are receiving increased attention. Traditional uses of wood, fibers, and chemicals derived from plants may be increased and, in addition, these materials may be substituted for mineral resources. The renewable resources are produced in heavily managed ecosystems that illustrate a unique set of interactions with environmental quality. Agriculture represents a nonpoint source of pollutants such as fertilizers, pesticides, sediment, and feed lot wastes. Forestry practices, such as clear cutting, are regulated for erosion control and esthetic considerations. Conversely, these managed ecosystems are adversely affected by other pollutants, particularly airborne contaminants such as ozone and sulfur dioxide. The increased acidity of rainfall, due to air pollution, can damage trees and crops and increase the mobilization of minerals from the soil. This set of environmental problems is, of course, little different from that encountered in agriculture for food production. However, any substantial increase in renewable resources for materials should take into account the associated environmental impacts.

Summary

The tensions between availability of materials and quality of the environment will increase with economic growth and the appreciation of environmental values. These tensions can be relieved to an extent by internalizing the costs of environmental protection so that they are reflected in the price of materials. Economic incentives and disincentives, such as effluent fees, are receiving renewed attention (*5*, pp. 49–51). In addition, government regulation to protect the environment will, perhaps arbitrarily, affect the availability and use of materials. The report, *Man, Materials, and Environment* (*5*, p. 25), concluded that:

> A national materials policy should be based upon the principle that calculations of benefits and costs associated with the extraction, transport, processing, use, and disposal of materials should take full account of the value of common property resources and of any change in the value of common properties resulting from the impact of materials on the environment, and should support the principle that those responsible for impairment of the environment should bear the costs of damage or repair. These principles should become a commonplace element of property rights, legislation, and administrative practice at all levels of government. The difficulty of measuring benefits and costs should not delay adoption of these principles but suggests the need for continuous observation and experimentation.

Environmental protection regulations will result in: (i) increased costs for many materials; (ii) disruptive changes in use of materials, due to environmental characteristics and revised cost effectiveness calculations; (iii) restrictions on the siting of processing and manufacturing installations; (iv) preemption of access and surface rights to some mineral bearing lands, particularly those that are federally controlled; (v) diversion of capital from new production facilities; and (vi) frustrating delays in decisions, such as those affecting leasing and plant siting.

In return for these generally undesirable disruptions in the continued development and supply of materials, society will obtain: (i) improved quality of air and water; (ii) long-term protection of the natural ecosystems of which man is a part; (iii) more efficient allocation of natural resources on the basis of more accurate and complete accounting of costs; (iv) improved human health through decreased contamination of the environment with toxic substances; and (v) conservation of materials through a closing of the production, use, and disposal cycle.

Ingenuity and a more complete understanding of the parts and interactions of the energy, materials, and environment system can do much to reduce the tensions in these conflicts and bring about equitable trade-offs among societal goals.

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Mineral Resources, Economic Growth, and World Population

We are running out not of mineral resources but of ways to avoid ill effects of high rates of exploitation.

David B. Brooks and Peter W. Andrews

One of the ironies of the limits-to-growth thesis is that, while purporting to present counterintuitive ideas about the future of the world economy, it has accepted one of the oldest propositions of resource economics (*1–4*). In its strongest form, this apparently commonsense proposition states that mineral resources will sooner or later run out, with drastic consequences for mankind. In a somewhat weaker form, it states that prices for minerals will rise sharply in the future. Much the same propositions are also put forward for energy and food supplies, but in this article we will focus on nonfuel mineral resources.

We maintain that most assessments of mineral supply, whether they are optimistic or pessimistic, are focusing on the wrong issue. We argue that while it is naive to jump from the premise that mineral resources are physically finite to the conclusion that this limits their economic availability, it is equally naive to jump from the premise that mineral resources are economically infinite to the conclusion that they could be produced in enormous volume without major social or political problems. This takes us beyond the usual studies of resource availability; such studies usually stop when the case for availability is proved, the investigators placing such implications as the effects on land use, the balance of payments, and the international distribution of income beyond the scope of their analyses. Yet we believe that these factors will prove less tractable than will the problem of supply itself.

Most of the data used in our analysis are from the United States or Canada. Not only are such data more abundant in these countries, but both the United States and Canada are high-income, resource-rich regions that provide prototypes of what one must look for elsewhere in the world. Our focus is on the next 50 to 75 years, not on some more distant future when populations will either have reached standing-room-only levels or population growth will have been completely curbed.

Mineral Supply

Although the ideas of resource scarcity and abundance are deceptively simple, difficulties arise when one tries to transfer them from the individual to society (*5, 6*). In a recent study, Fischman and Landsberg pose nearly a full page of questions that indicate just how difficult the concepts are to define. Notably they ask (*7*, p. 79):

> What is a "shortage," and what is "adequacy"? Is the supply of a given mineral "adequate" only if it continues to be forthcoming in the "required" amounts at present relative prices, or at prices rising no more rapidly than has been the trend, even if that trend reflects increasing supply stringencies? What if the only means of avoiding marked price change is the initiation of unaccustomed efforts at conservation, reuse, and recycling, or the making of major investments toward technological advance? Is adequacy measured in terms of current levels of minerals exploration, evaluation, and development, or trend levels? May a mineral be considered adequate just because it can be geologically inferred to exist in sufficient quantity, even if it takes major new outlays in exploration, evaluation, and development to find this quantity and get it into production?

These questions are not relevant exclusively to minerals. There are examples of such presumably renewable resources as fish and timber that have been totally exhausted, while presumably nonrenewable resources like minerals seem to be producible almost without end. In fact, analysts who have reviewed the issue carefully have not found many conceptual differences among natural resources on the basis of their renewability (*8*). Nor have they been able to demonstrate any overall tendency toward increasing scarcity (open space and timber are exceptions) in terms of higher real costs of production (*9*). Let us therefore look at minerals more carefully to see how these general conclusions apply to them.

The literal notion of running out of mineral supplies is ridiculous. The entire planet is composed of minerals, and man can hardly mine himself out. Except for a few substances, notably crude oil and natural gas, which are discretely different from the rock masses that contain them, the quantities of mineral materials in even the upper kilometer of the earth's crust approach the infinite in size. A single cubic kilometer of average crustal rock contains 2×10^9 tons (metric as elsewhere in this article) of aluminum, over 1×10^9 tons of iron, 800,000 tons of zinc, 200,000 tons of copper. Much the same sort of calculation can be made for seawater. We are not suggesting that such dilute materials will ever be mined, but only indicating that exhaustion in a physical sense is meaningless.

Of more immediate interest is the fact that some of the elements that are most important to society are available in the greatest quantity. Copper and zinc are relatively rare metals. Iron and aluminum are not; together with a few other elements, they make up much of the crust of the earth, and there are thousands of square kilometers that could be considered as low-grade iron and aluminum deposits, some of which will be mined in the future. Much the same can be said about phosphorus and potassium, the two critical mineral components for fertilizers (*10*).

Further, there is a strong tendency for many mineral resources to increase in quantity as the quality that can be economically exploited goes down. In general terms this means that there are greater volumes of deposits containing 0.5 percent copper than 0.6 percent copper, and greater volumes containing 35 percent iron than 40 percent iron, and so on. This relationship holds until, at a certain grade, the increased tonnage of contained metal obtained with unit decreases in grade reaches a peak. Beyond this point it falls with further decreases in grade, but such grades are typically well below those being mined today. Exponential curves for grade of deposit plotted against tonnage of contained metal have been drawn for manganese, aluminum, titanium, nickel, lead, zinc, and columbium (*11*), and they indicate that this tendency is by no means confined to a few commodities, as is sometimes asserted (*4*, pp. 80–82). However, it does not hold for all deposits nor for small regions, so careful interpretation is required.

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In short, almost every bit of evidence we have indicates the existence of vast quantities of mineral resources that could be mined and, further, that either as their price goes up or as their cost goes down (which is to say, as technology of extraction improves), the volume of mineable material increases significantly—not by a factor of 5 or 10 but by a factor of 100 or 1000.

The real question, then, is not whether resources exist but at what rate different sources of supply will become available to man in the sense of becoming economically feasible to recover. Natural materials do not become resources until they are combined with man's ingenuity. Over time the record is impressive. Mineral resources have become more and more widely available despite (and partly because of) growing rates of consumption. This, in crude form, is the modern economic view of mineral resources, or the "cornucopian" view as it has been dubbed.

Unfortunately, most descriptions of mineral resources include only the material that could be mined at today's prices and today's technology—what is properly termed "reserves"—and thus they understate the availability of these resources (*12*). The difference between reserves and resources become critically important when one is dealing with the so-called life index, the ratio of the reserves of some element to its current consumption. The resulting figure is best regarded as a sort of inventory of stock on the shelf, so to speak, but it is sometimes mistakenly taken to mean the years remaining until exhaustion. In fact, the ratio tends to remain stable over time. As shown in Table 1, mineral reserves in Canada have grown roughly in proportion to mineral production except in cases (see asbestos and natural gas in Table 1) where institutional changes have been taking place in the industry.

Fig. 1. Consumption of minerals throughout the world. Solid bars indicate estimated world consumption to the year 2000. Unbroken lines show current reserves at indicated prices. [From Cloud (*13*)]

Let us review the situation for the world as a whole. Some data supplied by Cloud (*13*) are instructive in this respect, for contrary to his emphasis, we find them reassuring. On the basis of the data in Fig. 1 (and other information), one foresees no problem to the end of the century in the economic availability of iron, manganese, silicon, aluminum, nickel, and certain other materials, including energy minerals (taken together). These commodities include most of those upon which modern economic life is based.

But what about the generations beyond the end of the century? Is there enough for them too? Consider the record of the past century during which mineral supply has kept well ahead of long-term growth in mineral consumption. Why should a process of technological development that has been operating so well come suddenly to an end? New development will of course have to come more rapidly with higher rates of consumption, but it can be argued that the steepest exponential curve of all is the growth of human knowledge.

There are two main dimensions to the economies of future mineral availability:

1) Geological extensions of supply through discoveries of new deposits and of new zones in old ones.

2) Technological extensions through the ability to work lower quality or less conventional materials.

In our judgment, future increases in mineral supply are going to come more from the latter than the former dimension, and this depends almost entirely on the growth of knowledge. The distinction is important: a new discovery adds a new mine to our stock of resources; a new technology for lower-quality resources can open up deposits across the world.

Therefore, it is simply not true, as is often remarked, that average rock will never be mined. As a matter of fact, in a few cases we are already mining commodities as by-products whose average grade in the ore deposit is lower than that in the crust (titanium mined in beach sands is an example). By exploiting technology as capital rather than the ore deposit (that is, land) as capital, the very commonness of the rock may be most attractive. The more common the rock, the more freedom one has to adjust the mine to the technology, rather than the other way around. In short,

through modest advances in technology mineral deposits become more rather than less available, and they can be mined in more rather than fewer regions.

Consider the case of nickel. Persistent price increases and generally rising worldwide demand for nickel are finally allowing the development of the lateritic nickel deposits, which had been known for years. These deposits are much more widespread than are the sulfide deposits typical of existing producing regions, and they are easier to mine. However, until recently there had been no commercially feasible way to extract the nickel from them. If one can judge from the success of several laterite mines in Third World nations, this is no longer a problem. As a result, world nickel reserves have been augmented manyfold and the nickel mining industry will be less concentrated geographically and industrially.

Table 1. Mineral reserves and mineral production in Canada: selected commodities, 1955 and 1969. Data from the Department of Energy, Mines and Resources, Ottawa.

Mineral	Reserves			Production		
	1955	1969	Ratio	1955	1969	Ratio
Petroleum*	2.75	10.5	3.8	0.13	0.41	3.2
Nickel†	6.0	8.5	1.4	0.17	0.26‖	1.5
Copper†	14.5	22.9	1.6	0.33	0.61‖	1.8
Iron ore‡	5.28	33.0	6.2	0.01	0.04‖	4.0
Zinc†	20.4	34.2	1.7	0.43	1.16‖	2.7
Natural gas§	16.6	53.4	3.2	0.15	1.98	13.2
Asbestos†	86.0	1200.0	14.0	1.06	1.61	1.5

*10^9 barrels †10^6 tons ‡10^9 tons §10^{12} cubic feet ‖Data for 1968 used for comparison because 1969 was a strike year.

Mineral Demand

Studies published in the past few years have, without exception, indicated that increased amounts of mineral commodities are going to be demanded in the future, mainly from the already industrialized nations but also from those nations in the process of industrializing.

The most comprehensive recent set of mineral forecasts is that made by the U.S. Bureau of Mines (*14*). World demand for primary, nonenergy materials was based on contingency forecasts and gave a spread of growth rates from 3.8 to 5.6 percent per year. Demand in the United States was based on specific forecasts of population and GNP (gross national product) growth, and gave a spread of growth rates from 4.2 to 6.0 percent per year. Some specific forecasts for the United States are shown in Table 2.

Another major study of mineral demand to the year 2000 (for the United States only) was made by Resources for the Future, using an input-output model together with various assumptions of population growth and productivity change (*7*). Some of these results, which tend to be lower than those of the Bureau of Mines, are shown in Table 3.

Using a method that was apparently first developed by the International Iron and Steel Institute (IISI) (*15*), the Mineral Resources Branch of the Department of Energy, Mines and Resources in Canada has initiated still another set of projections. This method, referred to as intensity of use analysis, suggests that demands for metals in the year 2000 may be lower, at least in industrialized nations, than the projections given by most other methods. Similar results have been obtained in the study recently released on behalf of the U.S. National Commission on Materials Policy (*16*).

The intensity of use approach uses both time series and cross-sectional information. For each country, the quantity of some material consumed per unit of national product (its intensity of use) is plotted against per capita income. The IISI study showed that, as per capita income increases in an economy, the intensity of steel use first rises also, but then it peaks and begins to decline. Absolute consumption of steel continues to increase because the decline in intensity is more than overcome by the increase in GNP, but the increase in consumption is less than is forecast by trend analysis. The level of income at which the intensity peak is reached varies by country, but for most Western industrial nations is close to U.S. $2000 per capita.

When we applied this method to nonferrous metals, similar peaked patterns were observed. Figure 2 shows some indicative results for primary copper and aluminum. Data for copper in the United States and Canada were plotted for the years 1926 to 1971, long enough to demonstrate clearly the rise and subsequent decline in intensity. (Fewer data were used in the study prepared for the U.S. National Commission on Materials Policy; hence, the patterns are less clear.) Intensity of copper use in the United States fits the "ideal" shape with the maximum occurring during World War II. In Canada, there was no fixed pattern prior to 1940, but after World War II the intensity of copper use clearly began to decline, although there were fluctuations corresponding to the major postwar business cycles.

Table 2. Demand in the United States for primary refined metal in 1968 and in 2000, according to the U.S. Bureau of Mines (*14*).

Metal	Demand (tons × 10^6)			
	1968	2000		
		Low	Median	High
Copper	1.4	4.4	5.8	7.2
Lead	0.8	1.2	1.9	3.6
Zinc	1.3	1.9	2.8	3.6
Manganese	1.0	1.7	1.9	2.1
Nickel	0.15	0.35	0.42	0.50
Aluminum	3.2	15.7	23.4	31.2

Table 3. Demand in the United States for certain metals in the year 2000, according to Resources for the Future (*7*).

Metal	Demand in the year 2000 (tons × 10^6)			
	Low population		High population	
	Low growth	High growth	Low growth	High growth
Copper	2.6	3.3	2.9	3.6
Lead	1.5	2.0	1.8	2.2
Zinc	2.8	3.5	3.2	4.0
Manganese	1.9	2.4	2.2	2.6
Nickel	0.29	0.36	0.33	0.40
Aluminum	11.9	14.5	13.0	15.9

The position of the Canadian curve above that for the United States probably reflects the export orientation of the Canadian economy because intensity of use is measured as shipments from refineries.

The implications of declining intensity of use can be seen by considering further the example of copper use in the United States. Figure 2 shows that the curve peaks at nearly 4 tons between U.S. $1700 and U.S. $1800 per capita (1961 dollars) in the late 1920's and again in 1940. If one ignores the distortions caused by World War II, the curve declines fairly uniformly to slightly over 2 tons at U.S. $2800 per head in 1959 to 1961, and then falls more slowly in the following decade to just below 2 tons at U.S. $3700 per head. If any decline continues, there are important implications for projections of consumption. The projections of GNP and population growth used by the Bureau of Mines indicate that a per capita income on the order of U.S. $7000 (1961 dollars) can be expected in the United States by the year 2000. At that level, consumption of copper could be, per million dollars of GNP: at 2.0 tons, 4.9×10^6 tons; at 1.5 tons, 3.7×10^6 tons; at 1.0 ton, 2.7×10^6 tons. The Bureau of Mines median contingency forecast is 5.8×10^6 tons.

The case of aluminum is more difficult. Its intensity of use curve is still rising in the United States, but the rate of increase has declined of late. The dashed lines on Fig. 2 represent three possible directions the intensity of aluminum use might take in the United States. By the end of the century, they are equivalent to consumption levels of 7.3, 16.5, and 22.2×10^6 tons, which can be compared with the Bureau of Mines median forecast of 23.4×10^6 tons.

These notes on future mineral demand only indicate that, as nations move into a postindustrial phase, their intensity of use of mineral commodities tends to decrease. The pattern for the currently less industrialized nations is less clear, and other variables would have to be studied before sound comments could be made on total world demand. However, it does not seem likely that the consumption of nonenergy minerals will continue to grow at past rates.

The Challenge to "Cornucopianism"

The idea that mineral supplies could be greatly augmented by technology has always been challenged by certain geologists. Recently, their views have been seconded by some systems analysts. Several of the conceptual and empirical aspects specifically related to minerals will be discussed briefly here (*17, 18*).

The challenge on geological evidence is based on several lines of reasoning. First, some analyses depend upon extrapolation of production trends along mathematical curves. However, production history is not based solely on the geologically available supply but also on institutional factors, such as military policies and the tariff structure. Second, other analyses are based on either individual mines or types of ore deposits that are characterized by sharp cutoffs between ore and country rock. Unquestionably, mines and such ore deposits can be exhausted, but this does not prove that world supplies are declining in an economically meaningful sense. Third, still other analyses are based on questionable ideas about the economics of discovery. While exploration costs more now than formerly, this is irrelevant. What is important is the cost per unit of information gained, and eventually of ore discovered, and this is not increasing inordinately (*19*). Moreover, it is hardly surprising that many deposits coming into production today were discovered years ago, for today's exploration is also turning up numerous deposits that will not be mined for some years.

Turning to the challenge stemming from systems analysis of the limits-to-growth type, our first comment is that it mistakes both the nature of and the evidence concerning the resource supply. Minerals are treated as if they came from a fixed stock, an approach that is not improved by the qualification that the reserve figures are perhaps off by a factor of 5 or 10. This qualification merely compounds the confusion, for we are really dealing with a flow, not a stock, and with a flow that responds to demand. True, we may have witnessed a long-term increase in the price of copper over the past 10 years, though institutional factors have obviously played a role as well. And for some commodities, perhaps tungsten, real shortages may develop (*7*, p. 93). However, such exceptions are far from proving that prices for many minerals will increase exponentially in the future under consideration here.

Our second comment is that the effectiveness of a price-cost system in altering the quantities demanded and supplied is ignored. Surely one cannot reasonably assume that mineral prices will continue to rise but that this will have no stimulating effect on exploration, technological development, and recycling (to say nothing of a damping effect on demand). However, those who challenge cornucopianism tend to ignore price effects, and let themselves open to the criticism that they did not deal with what, for all of its defects, is an effective adjustment mechanism (and one that can be applied whether the price derives from a market in a capitalist system or from a central bureau in a socialist system).

Finally, the challenge stemming from the nature of demand is also mistaken. While we have seen dramatically increasing demands for minerals over the past several decades, this does not mean that such increases have been or will continue to be exponential. As shown above, more sophisticated analyses suggest that relative demands decline after a point with increase in per capita income. Indeed, even though absolute increases in quantities demanded are still enormous, the relative growth is sufficiently damped that it was suggested in one study that mineral production will need to grow less fast in the future than it has grown in the recent past, exactly the opposite of most conclusions based on trend analysis (*16*, pp. 38–40).

"Cornucopianism" Saved

The foregoing combine to cast considerable doubt on the whole idea that mineral resources will limit growth. For the model itself, this creates a very weak link in the causal chain (*20*). Thus, one must ask whether we have learned anything new from recent challenges to cornucopianism. Our conclusion is that we have not, but we have been forcefully reminded to ask some important questions.

We thus maintain that minerals can be made available (at prices not greatly different from those today) to satisfy demands that are growing because of population growth, higher per capita incomes, and changing technology. In the discussion that follows we will assume that these minerals are produced and will ask about some of the implications of producing them, rather than focusing on their physical or economic availability.

Pollution

Perhaps the most widely recognized undesirable effect of higher rates of resource production and consumption is the increase in pollution that must result. In saying this, we are well aware of the major improvements being made in pollution technology that will permit mines and smelters to produce less effluent per ton of production, and transport facilities to spill less per ton-mile, for example. However, to obtain a significant improvement in the environment, such changes in pollution technology will not be sufficient. The decrease in effluents per unit of production or of consumption must more than overcome the increase in production or consumption

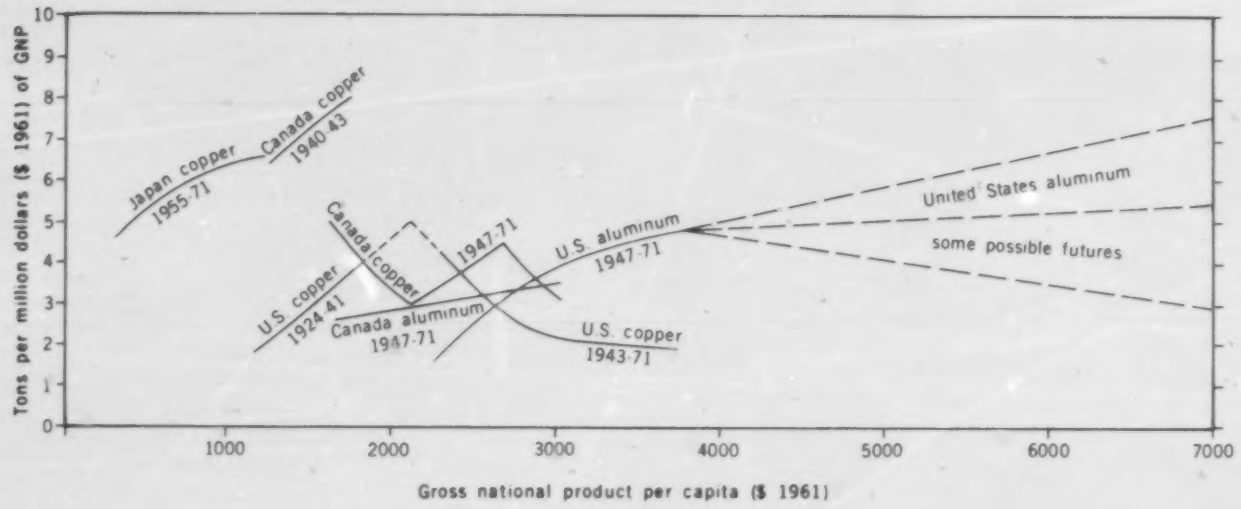

Fig. 2. Intensity of use of copper and aluminum: examples from Canada, Japan, and the United States.

itself. Moreover, as the scale of production increases, so will the impact of any miscalculation or accident (which are inevitable). Thus, we can either strive continually for technologies that will so reduce pollution that it will be possible to produce (and consume) safely whatever we want, or we can aim to reduce growth to make the technological task of environmental improvement less expensive and less frenzied.

There are two additional aspects of pollution that are less amenable to technological solutions: the chronic low-level exposure of the human population to pollutants that is all but inherent in an industrial world, and the possibility of triggering an ecological catastrophe.

Much pollution control practice has been based on the theory that there are "thresholds" below which health is not affected. We know now that, for many pollutants, including radioactivity and lead, thresholds do not exist. Chronic low-level exposure is important; for every additional unit of a pollutant, someone's life is shortened or days of sickness are lengthened (*21*). Since some escape of such substances cannot be avoided, the more we introduce to the environment, the less we implicitly value human life.

At the other end of the probability scale, it is conceivable that man could touch some physical or biological lever that would prove globally catastrophic. Fortunately, such problems are less likely to stem from nonfuel minerals than from energy production and consumption (*22*). Even the more difficult problems, such as acid mine drainage and smelter-based sulfur oxides, tend to be local or regional in scope rather than national or international. Nevertheless, however small the probabilities they bear close surveillance as part of the Earthwatch program originating at the 1972 United Nations Conference on the Human Environment (*23*).

Extensive Land-Use Change

In speaking of pollution we have referred to effluents added to air, water, or soil. Somewhat different, but at least as much at issue in many mining regions, are the land-use changes that will be necessary if higher rates of production are to be achieved. For example, the surface mining debate in most places is much more a question of appropriate land use than it is of pollution.

However, given that resources are irregularly distributed, the demands for efficiency and for large-scale production will dictate that resources be produced wherever they are found and by low-cost methods. Demands for land to be used for ecological preserves, recreation, and agriculture are likely to take second place to demands for land to be used in mineral production. For example, resources located in the Arctic or in other untouched areas will have to be extracted, as will deposits of common materials (sand, gravel, rock) located near urban areas. Moreover, the production goal will be to economize on manpower and materials and perhaps on energy, but at the expense of consuming, and sometimes irreparably altering, the land surface. Such tendencies will be aggravated because, as grade becomes lower, more and more mining is required to recover the same volume of valuable metal or mineral. Thus, we have the proposals for using nuclear energy to fracture underground ore bodies or to remove the overburden from ore bodies near the surface (*24*). The very scale of such an effort, coupled with the need to prevent the public from entering large areas for reasons of safety, implies enormous land-use change.

Most land-use changes under discussion here cannot be solved technologically. While the effects of some of these changes can be mitigated (by using underground quarries near urban areas, and by surface reclamation, for example), many land-use decisions are all but irreversible and "simply" involve questions of value.

Increased Energy Consumption

Another penalty for using lower-grade ores will be the increase in energy consumption per unit of output because of the lower concentration of valuable material per ton. This increase will be still greater because some of the new sources will require finer crushing or will be more refractory than previously mined ores (*25*), though this effect might be offset in part by less energy being required for the actual mining of the ore (as with the laterite nickel ores described earlier).

Having recognized this problem, however, there is relatively little more one can say. If energy costs go up, as they seem likely to do, technology will turn toward cheap sources of energy and to ways of conserving energy in production. For example, the use of nuclear explosives as described in the preceding section offers a relatively inexpensive and efficient way of using energy in mining. Moreover, it seems ridiculous to point to mineral production as a cause of such global problems as changes in heat balance or climate. Mineral production is responsive to, not creative of, the demand for consumption, and

by about the end of the time frame under consideration here, the world must find a way to deal with this aspect of the energy problem in the widest sense (*26*).

Instability in Human Settlements

The expansion of mining is closely associated with certain problems of human settlements. The broadest issue is that the introduction of mining can be a sociological shock. For example, some of the objections to proposals for copper mining in Puerto Rico are based on the cultural change that mining would impose on a now rural and largely self-sufficient region (*27*). Much the same objection has been raised with respect to the Inuit (Eskimo) in the Canadian North. Even less than land use can these issues be resolved technologically. Most often they require all-or-nothing decisions based on the society's values.

Most mining communities, and all of those that cannot eventually find an alternative economic base, have a limited life. Moreover, few of them have been attractive places in which to live; in many instances they have been treated as "camps" to be abandoned as soon as the mine is closed, or they have been built as oppressive company towns. Even if mining communities are more carefully planned today, their inherent tendency to deplete their reason for existence cannot be ignored, because the result is often a depressed region with high unemployment and few services. Such problems are intensified by the cyclical nature of investment in minerals, so that there tend to be cycles, every 20 to 40 years, during which a nation is faced with waves of mine closures.

International Distribution of Income

In stating that mineral resources were unlimited, we deliberately made no distinction between the industrial and the nonindustrial areas of the world because there are enough resources for all. However, contrary to what one might expect, increased competition for minerals is likely to work against rather than for the primary producing nations. If, as we have supposed, production-consumption trends are going to continue rising, it seems excessively heroic to suppose at the same time that the future distribution of returns is going to be very different.

For one thing, the linkages between mining and other sectors of the economy are relatively weak. A mine alone, or even a mine associated with a smelter and refinery, does not confer large benefits upon a society in terms of direct or indirect employment and income unless manufacturing industries are developed that consume the products of the mine (*28*). In fact, most development economists now believe that natural resource development usually results from activity in other sectors of the economy (or other regions of the world), and that resource development itself seldom initiates other industrial development (*29*). For example, Chilean economists have pointed out that most of that nation's rail system, extensive though it is, was designed to move copper from mine or smelter to port and has done little to stimulate development or to integrate the country.

For another thing, although a rising demand for a resource may mean that the price of the commodity can be increased, the actual amount by which it can be increased is very limited. The economic rent collectable by the producing country or organization cannot be increased indefinitely as is sometimes implied.

The Organization of the Petroleum Exporting Countries (OPEC) has succeeded in raising oil prices and national revenues. But OPEC remains a unique example, successful because of the military and commercial demand for petroleum, the difficulty of storing it, and the concentration of production in a region where the populations have a common ethnic background. Moreover, it is easier to find substitutes for other mineral commodities than it is for petroleum. Technological developments enable us to utilize lower quality, and hence more widely occurring, mineral resources (as with taconites) and also enable us to use more common materials in place of rarer ones (as with ceramics and plastics to replace metals). But such developments favor industrialized regions, which of course also fund most of the research. Therefore, while the copper and iron ore producing nations, for example, seek to gain more revenue, it is an open question how far they can reproduce the OPEC model.

For much the same reasons, there is unlikely to be any great shift of political power because of the irregular distribution of mineral resources. When more powerful nations desire resources that are located outside their own borders, they will find ways to obtain them. In some cases this may be a matter of their using crude 19th-century imperialistic techniques. In other cases, they may apply their own national laws extraterritorially or impose direct sanctions on the countries that have the resources. However, political power over resource suppliers will most commonly be exercised through the subtler means of economic domination. While by no means uniformly imperialistic, such measures as direct foreign investment, special trading arrangements, and bilateral aid, when used by powerful nations or blocs of any economic system, do tend to induce more acquiescent behavior among resource-supplying satellite countries. As several recent white papers indicate, this sort of approach is common and could prove to be a significantly destabilizing force in international relations.

Conclusions

World population and world income can grow at any likely rate for the next 50 to 75 years, probably for longer, and mineral supplies will continue to keep pace with demand. Not, however, without environmental costs, without affecting Third World development, and, perhaps most important, without ignoring critical questions of power. In what might be termed the revisionist form of the limits-to-growth thesis, Aurelio Peccei and Alexander King, cofounders of the Club of Rome, seem to be saying that the forecasts of doom themselves are unimportant but they symbolize critical problems of the nature and uses of power in the modern world (*30*):

> . . . the Club of Rome is questioning the quality of growth and its distribution around the world. . . . We know that the present structure of the world is obsolete. . . . Both private and state capitalism are stale . . . we have to develop something else.

Surely, continually increasing rates of mineral production are symptoms of this obsolete power structure, a result of the fact that, ultimately, population growth and monetary income growth lead to demands for natural resources that necessitate their being found and produced regardless of the implications. Since such higher rates of production are geologically and economically sustainable, we should choose among alternative paths of growth, and hence among alternative rates of mineral resource development, according to what we like or dislike about these implications. The key information will not be found in tables comparing reserves and consumption but in preferences and ethics.

References and Notes

1. The best-known treatment of this thesis is the Club of Rome MIT study by Meadows *et al.* (see *2*, pp. 54–69). See also "Blueprint for survival," *Ecologist* **2**, 1 (1972). For a more technical treatment of minerals see Lovering (*3*) and Cloud (*4*, pp. 71–88). For a quasi-official U.S. government view of mineral supply, see National Materials Advisory Board, *Elements of a National Materials Policy* (Report NMAB-294, U.S. National Materials Advisory Board, Washington, D.C., 1972).
2. D. H. Meadows, D. L. Meadows, J. Randers, W. W. Behrens III, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind* (Potomac Associates Universe Books, New York, 1972).

3. T. S. Lovering, in *Resources and Man: A Report by the U.S. National Academy of Sciences*, P. Cloud, Ed. (Freeman, San Francisco, 1969).
4. P. Cloud, in *Environment, Resources, Pollution and Society*, W. W. Murdoch, Ed. (Sinauer Associates, Stamford, Conn., 1971).
5. Much of this section is based on material presented in "Mineral supply as a stock," see Brooks (*6*).
6. D. B. Brooks, "Mineral supply as a stock," in *Economics of the Mineral Industries*, W. A. Vogely, Ed. (American Institute of Mining, Metallurgical and Petroleum Engineers, New York, 1976). [Part of this work was published previously in *Minerals: An Expanding or a Dwindling Resource*, Mineral Resources Branch, Mineral Bulletin 134 (Information Canada, Ottawa, 1973)].
7. I. L. Fischman and H. H. Landsberg, in *Population, Resources and the Environment: A Report to the U.S. Commission on Population Growth and the American Future*, R. G. Ridker, Ed. (Government Printing Office, Washington, D.C., 1972). [The approach and general conclusion of this study, probably the best of its kind, are summarized by J. L. Fisher and R. G. Ridker, *Am. Econ. Rev.* **63**, 70 (May 1973)].
8. A. Scott, *Natural Resources: The Economics of Conservation* (Univ. of Toronto Press, Toronto, 1955).
9. H. J. Barnett and C. Morse, *Scarcity and Growth* (Johns Hopkins Press for Resources for the Future, Baltimore, Md., 1963). See also the brief discussion by C. Morse, *Am. Econ. Rev.* **63**, 126 (May 1973).
10. The case of phosphorus has become something of a cause célebre after the publication of a report which stated that phosphorus resources would be exhausted before the 21st century [Workshop on Global Ecological Problems, *Man in the Living Environment* (Institute of Ecology, Madison, Wis., 1971)]. However, if one includes only the already identified resources, there is sufficient phosphorus to refute the Institute of Ecology figure [G. D. Emigh, *Eng. Mining J.* **173**, 90 (1972)].
11. The most extensive discussion of the application of grade-tonnage relationships to mineral resources is by Musgrove who prepared an appendix to the article by Brooks (*6*).
12. The terms resources and reserves are properly defined for minerals by J. Zwartendyk, *What Is "Mineral Endowment" and How Should We Measure It?* (Mineral Resources Branch, Mineral Bulletin 126, Information Canada, Ottawa, 1972).
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Tapping Resources in Municipal Solid Waste

S. L. Blum

In recent years, municipalities have confronted increasing constraints in the collection and disposal of their wastes. Disposal costs and waste quantities have risen significantly, and environmentally acceptable disposal options are becoming limited, particularly in urban areas, as suitable landfill sites become unavailable, environmental restrictions are imposed, and public sensitivities to aesthetics become heightened.

Historically, cities have disposed of municipal refuse by either burning or burying it. It is becoming evident that alternatives are needed; the quantitative impacts are staggering. The national cost of collection and disposal of refuse was well over $6 billion last year and was the third largest expenditure funded from local revenues. Since these activities are labor-intensive, it is expected that costs will continue to rise rapidly. Similarly, the quantity of refuse has increased by about 8 percent in the years 1971–1973 (Table 1) and the per capita generation has increased from 3.3 to 3.5 pounds (*1*). About 75 percent of the total population is now found in urban areas, a growth of about 4 percent in the last decade; this makes land available for disposal difficult to obtain in most large cities. New regulations on emission control—involving NO_x, SO_x, and particulates at present, and most likely including halogens and heavy metals in the near future—are making most of the 150 or so existing municipal incinerators obsolete. Although difficult to estimate, the cost of upgrading these incinerators to meet emission requirements in the next 5 years may approach $500 million. There have also been real doubts about whether sanitary landfills offer an acceptable solution. For the most part, these landfills have been far from sanitary; it is estimated that leaching from most landfills that lack an impervious bottom may give rise to biological oxygen demand loadings on the same order of magnitude as that dumped into all streams in a given year.

Sanitary collection and disposal have been a responsibility that municipalities have traditionally assumed and apparently will continue to assume. Two studies by the National League of Cities (*2*) indicate that half of the nation's cities will be running out of current disposal capacity in 1 to 5 years, and that municipal officials felt that the problem of solid waste management was the most urgent issue facing them in 1973.

From the broader, national perspective, we might ask whether the problems of municipal waste disposal be translated into an opportunity for reclamation of valuable materials resources in the waste stream. An increasing need for raw materials has given rise to more active exploration of additional sources of supply. There has been renewed effort in locating sources of baux-

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ites and related ores for aluminum production; copper, nickel, and chromium exploration is continuing; and the public is becoming increasingly aware that raw materials play an important role in the national economy. Recent events leading to oil limitations and what appears to be economic collusion by some nations supplying raw materials have further underscored the importance of raw materials. Strategies for minimizing dependence on a raw material may range from increasing its removal rate from the earth to substituting other materials, recycling existing material, or finally doing without it. This article will focus on the recycle component, and will attempt to show where we have been and where we might be going in recycling of post-consumer waste, or municipal solid wastes (MSW).

Many environmentalists display an enthusiasm for recycling that borders on religious intensity. There is a time and place to recycle; not all recycling is good, nor is the absence of it bad. At the present time the primary motivation for recycling is a buyer-seller relationship. However, if "total community benefit" is considered, there are times when it is beneficial to recycle although it may not be economically advantageous to the individuals involved (*3*). This is the area in which government has to decide what its role should be.

One can generally predict that as affluence increases, the amount of waste disposed will also increase because we use more things, we throw away rather than repair, and convenience packaging gives rise to more waste. For every dollar of gross national product, about 1/3 pound of municipal waste is discarded in the United States. This has been relatively constant over the past 15 years. In 1972, the weight of basic raw materials used per capita in the United States was 42,500 pounds at a value of $237 per capita. Of this amount, the metals comprised 3 percent by weight but represented about 25 percent of the total value. It is clear then that there is economic motivation to recycle metals. The availability of viable markets and the ease in removing commodities from the waste stream determine the degree of recycling.

Recycling of MSW is being done on a small scale and in 1973 amounted to about 9.4 million tons or about 7 percent of the gross discards (*4*). Containers and packaging contributed 5.3 million tons and nondurable goods such as paper and books, 3.8 million tons; the remainder consisted of appliances and tires (durable goods). The processes and techniques shown in Fig. 1 are newly developed; although they have been little used in recycling, they will be discussed here because of their future promise. Recycling of interindustry scrap rather than intraindustry scrap (home scrap) will be emphasized, with the focus on processes to produce energy and recover material.

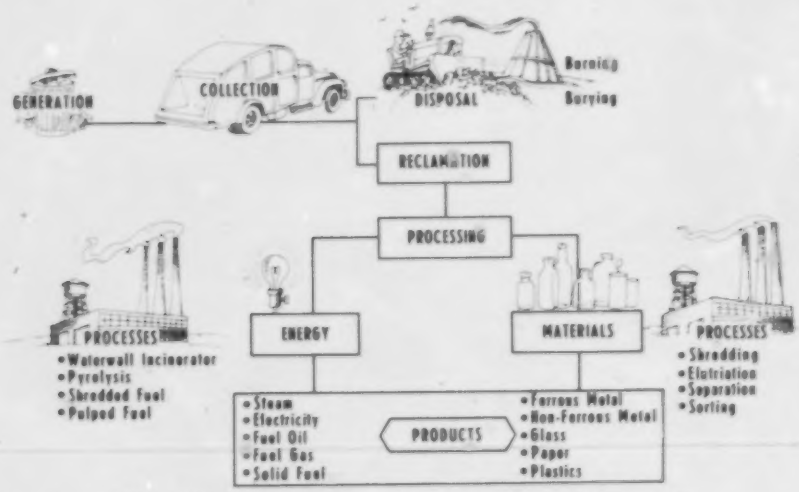

Fig. 1. Processing and products in treatment of municipal solid waste.

Table 1. Consumer solid waste for 1971 and 1973 (as-generated net weights). [Source (*4*)]

Materials	Generation		Growth (1971–1973)	
	1971 (10^6 tons)	1973 (10^6 tons)	(10^6 tons)	Percent change
Paper	39.1	44.2	5.1	13.0
Plastics	4.2	5.0	0.8	19.0
Rubber and leather	3.3	3.6	0.3	9.0
Textiles	1.8	1.9	0.1	5.5
Wood	4.6	4.9	0.3	6.5
	53.0	59.6	6.6	12.4
Metals				
Ferrous	10.6	11.0	0.4	3.8
Aluminum	0.8	1.0	0.2	25.0
Others	0.4	0.4	0	0
	11.8	12.4	0.6	5.1
Glass	12.0	13.2	1.2	10.0
Subtotal:	76.8	85.2	8.4	10.9
Food waste	22.0	22.4	0.4	1.8
Yard waste and miscellaneous	25.9	26.9	1.0	3.8
Total (not recycled)	124.7	134.5	9.8	7.9
Total recycled	8.0	9.4	1.4	17.5
Total generated	132.7	144.9		

Materials Recovery Systems

At the present time, 93 percent of MSW is disposed in landfills, dumped in oceans, or burned. Although recovery from landfills is possible, it can be very expensive. The flow of material from generation to use is shown in Fig. 1. Materials can be separated and reclaimed at various points before processing; for the most part, reclamation involves fairly simple techniques (*5*). The term front end separation is often used to describe the physical removal of materials before a main processing operation. Rear end separation refers to the same techniques after the main processing has taken place. The reclamation process, as shown, has two main goals: energy and materials recovery.

Nature, through a series of geologic processes, lays down concentrations of materials that we can recover as ores if they are not diluted too much for economic recovery. A somewhat similar process occurs in the generation of waste and its recovery. We probably have the technology to recover most components of refuse, but it is not always economically attractive. For illustration, consider the case of a father and his 5-year-old child who, after walking several miles on the beach, opened their lunch of peanut butter sandwiches. The child dropped his sandwich in the sand. They were too far to go back to their car for re-

serves, and the problem involved the alternatives of cleaning the sand from the sandwich or going without lunch. It was technically possible to remove the grains of sand or to eat the sandwich with the expectation of not getting ill, but was it worth it? If the situation is difficult enough and we need raw materials we can recover them by recycling everything used, but is it worth it now or when will it be worth it?

We can affect the generation of waste by adjusting the quality and quantity of refuse. This can be accomplished by restricting the type of materials discarded, creating incentives to reduce generation, or increasing the useful life of finished products. After collection we can develop distribution network techniques that will, for any given geographic location, optimize the flow of materials to minimize distances and store material in transfer stations for processing. At this stage, the material is handled and treated as bulk refuse with variations in paper and container separation possible. The collection process, although estimated to involve 80 percent of the costs of MSW treatment, is a subject in itself; although involving technology it is primarily institutional in nature. The processing stage is of most interest to the recovery of energy and materials.

The material to be processed is bulky, wet, and smelly, yet somehow we must separate it and remove the valuables. Separation processes are designed around the properties of the materials, including physical, chemical, thermal, electrical, and magnetic. Figure 2 details a scheme for materials recovery separating organics, glass, and metals (*6*). In front end separation there are common problems of interest, such as shredding and classification, which require more study because of the heterogeneous nature of the refuse and its abrasive qualities. The U.S. Bureau of Mines has done much work in this area, and many of the processes and techniques used domestically were either developed or explored by them (*7*).

Material recovery techniques for paper and metals have been used in the scrap industry for some time. The amount of metals recycled in 1972 is shown in Fig. 3 (*8*). Although iron, tin, and aluminum dominate the metals presently recovered from MSW, there are markets and technical potential for some of the other metals shown. A viable industry for secondary materials recovery plays the role of middleman between scrap producers and scrap users. We thus have an institutional arrangement that can be of great value in handling materials generated through the processing of MSW. There are various incentives to recover these materials: recovery helps in the conservation of natural resources; helps reduce land requirements for disposal; helps in the preparation of waste-based fuel for energy recovery systems; and helps conserve energy by decreasing the energy required in winning and smelting of primary metals by substituting recycled for virgin materials. It has been estimated, for example, that 200 million Btu/ton can be saved in the use of recycled aluminum for virgin aluminum, 12 million Btu/ton for iron, and about 1.2 million Btu/ton for glass (*9*).

Separation of materials for recovery depends on the stage in the process in which they are removed and, most importantly, on the properties of the material. Iron, for example, is magnetic and can be separated after shredding either by front end processing or later, for example, after incineration. The quality of the material and the level of impurities will be different in each of these cases. The markets for the separated materials will drive the separation techniques. In most cases where energy is the prime recovery objective, the materials recovery follows rather than leads the process. However, it is expected that as the value of the materials goes up in the marketplace, the processing can and will be adjusted to recover materials in which the cost benefit is greatest.

Copper, for example, with a specific gravity of 8.9, can be separated from aluminum, with a specific gravity of 2.7, by

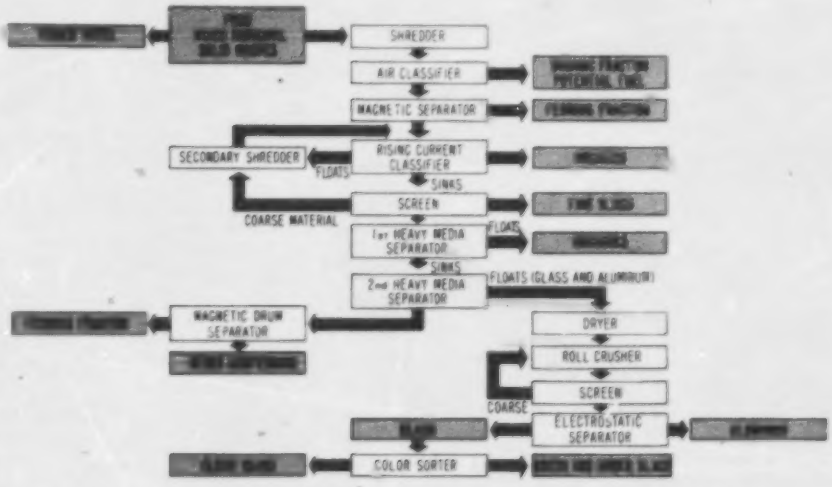

Fig. 2. Processing scheme for separating materials from mixed refuse. Organics, glass, and metals are represented by shaded areas. [Source (*6*)]

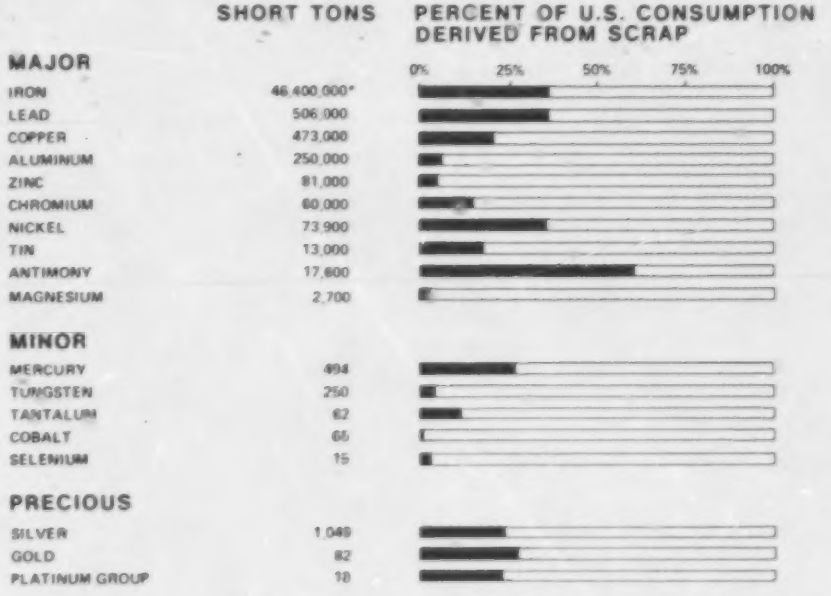

Fig. 3. Scrap recycled in the United States, 1972. Significant amounts are being recycled, and further improvement is possible. [Source (*8*)]

liquid media separation. It is nonmagnetic and separable from iron by magnetic methods. Techniques are being developed to separate it by dielectric means from other nonmagnetic materials such as aluminum, tin, lead, paper, and polymers. Its color can be used to separate it from the bronzes and brasses by optical techniques. At cryogenic temperatures it remains ductile and does not fracture in a brittle fashion as does iron. This difference in fracture behavior allows for recovery by shape and size of the processed material. As more recovery systems come into use and experience is gained, the technical feasibility can be further tested and the economic viability determined in real market conditions.

Materials that currently have the greatest interest for recovery are ferrous metals, aluminum, and paper. Contents of the MSW stream before and after incineration are shown in Table 2, as is analysis of the metal portion recovered along with the iron in magnetic separation. One has to look at this type of analysis in the same fashion as the mining engineer analyzes an assay of a potential ore. In fact, one can consider MSW as an "urban ore" and follow its assay from location to location and also for a long time period during which its composition may change. These changes may be caused either by the purchasing tastes of the public, which can alter the composition of MSW, or by the choice of disposal techniques, which might concentrate given materials in an area where special beneficiation methods are warranted. The techniques for processing of ferrous metals, aluminum, paper, plastics, and fuel are described because these are the materials which are expected to dominate the recovery scene in the next 5 years.

Ferrous Metals Recovery

The recovery of ferrous metal from MSW is based on magnetic separation. Two types of magnetic separators are primarily used: suspended and pulley. These devices are usually used in tandem, with the suspended-type pulley removing the larger pieces after an initial shredding. The material is then divided by air classification into light and heavy fractions, and the pulley-type separator is used in the heavy fraction.

Two basic problems have been evidenced in operation: ferrous losses in the light fraction resulting from air classification, and impurities (slag, tin, and copper) which make it unacceptable to scrap users. Magnetic separation as now used has about 90 percent efficiency in the recovery of ferrous metals. Newer experimental separation techniques that have been developed either use a sink/float mechanism for separation or a fluid containing finely divided magnetic material whose apparent density can be varied by the imposition of a magnetic field. These fluid techniques have not been employed on a large scale as yet in any of the operational plants but may offer a degree of "fine tuning" if needed.

In 1973 it was estimated that about 11 million tons of obsolete steel scrap was generated in municipal waste; this does not include items such as automobiles which are not considered as part of the MSW stream (*4*). Steel cans made up about half this volume (5.6 million tons), and it is estimated that about 70,000 tons were recycled, or 1 percent of the potential. Steel cans, commonly called tin cans, are composed of about 99 percent steel. Four main uses for salvaged cans are as a precipitation agent in a leaching process for the beneficiation of copper ore, as a source of tin in chemical detinning processes, as a source of scrap iron in steelmaking, and as a raw material in producing ferroalloys.

Table 2. Composition of municipal solid wastes. [Source (*14, 15*)]

Component	Analysis (as received percent by weight)
Before incineration (14)	
Moisture	25.1
Carbon	25.2
Hydrogen	3.2
Oxygen	18.8
Nitrogen	0.4
Chlorine	
Organic	0.16
Inorganic	0.14
Sulfur	0.1
Ferrous metals	7.8
Aluminum	0.6
Other nonferrous metals	0.3
Glass, ceramics	12.2
Ash	6.0
Total	100.0
After incineration	
Iron*	30.5
Nonferrous	2.8
Glass	49.6
Ash	17.1
Total	100.0

**Analysis of magnetic portion picked up and in iron (15)*

	Average weight (%)
Carbon	.02
Sulfur	.03
Manganese	.01
Phosphorus	.03
Tin	.17
Copper	.44
Chromium	.09
Nickel	.10
Molybdenum	.02
Lead	.10
Total	1.01

Copper processors used about 70 percent of the available steel cans in the MSW stream. About 2 to 3 pounds of iron are needed to produce 1 pound of copper in this process. The quality of the cans is not too significant as long as maximum surface area is available for the solution to permeate. It appears that cans that have been incinerated are acceptable for this process, and the bimetal can with an aluminum top offers little problem of a chemical nature.

The techniques involved in detinning, however, require that the cans be clean and the tin not be alloyed with the base metal, as would occur if cans were incinerated at temperatures above 450°C. Detinning by solution involves the use of a hot solution of caustic soda and sodium nitrate; tin is recovered from the sodium stannate formed. Techniques for removing labels, waxes, and greases from cans can increase the desirability for use by detinners.

The use of cans in various steelmaking processes is moving more slowly than would be expected. Steelmakers have always been reticent to use scrap materials whose exact compositions are unknown and whose use may create problems in their melting or forming techniques. It also appears desirable to mill scrap so that it balls up and flows freely when loaded into a furnace (densities in excess of 80 pounds per cubic foot are desirable). The chemistry of the batch must be carefully controlled, and unknown quantities of lead, tin, and aluminum can create difficulties. For example, aluminum can cause slag problems in a basic open hearth furnace and pinhole problems in casting if not removed prior to melting. The most profitable market for scrap appears to be in No. 1 dealer bundles of scrap iron whose price has varied from $75 to $120 per ton in the past year. Careful selection and detinning usually provides such a product.

The three basic facility types used in steelmaking and the typical percentage of scrap used in each process are as follows: basic oxygen furnace, 30 percent; open hearth furnace, 40 percent; and the electric arc furnace, 98 percent. The increasing use of electric arc furnaces and the construction of minimills near large cities with ample scrap supplies will further open markets for steel scrap. Although impurity levels appear to be very significant in limiting use at the present time, there are techniques that can minimize these problems. Careful batch control and dilution have been used by some melters to minimize the

effects of copper and tin. Research is also being done on techniques of using scrap and minimizing the effect of impurities by slag control, melting techniques and holding times, and modified forming techniques.

Nonferrous Metals Recovery

The nonferrous metallic components of MSW are by far the products with the highest unit value. These constitute about 1 percent of the generated waste stream or approximately 1.4 million tons in 1973. This represents a growth of about 25 percent in the 2-year period (1971–1973), but of this amount only about 4 percent was recycled and recovered. Aluminum makes up the highest percentage of these metals. The main techniques for its recovery are in early stages of development and have not yet been fully demonstrated on a large scale. Shredding, air classification, and magnetic separation and screening all yield material for further treatment by these processes. The main processes under consideration depend upon various properties of aluminum: its density, dielectric and magnetic properties, and melting point.

As the amount of aluminum recycled increases, there may be a series of technical problems. Lead and tin are introduced as solder impurities in cans. If present in melts, each of these components can segregate at grain boundaries during cooling, which tends to weaken the metal (9). Iron can be added as a dispersion hardener to aluminum in very small quantities, but quantities greater than 1 percent cause problems, especially in casting. Glass contamination can create difficulties in a molten aluminum bath by being slowly reduced with the release of free silicon, which can react with magnesium. The magnesium is usually added as a hardener, and the silicon-magnesium reaction reduces the effectiveness of the magnesium. Zinc addition causes casting problems as does copper. After alloying, it may be extremely difficult to remove the alloying elements, hence care must be exercised in controlling such additions. The present recovery of aluminum is primarily for low grade applications. Techniques for impurity removal are needed, and more research may be able to solve these problems.

The other nonferrous metals found in small quantities in MSW offer potential for recovery but in many cases the technology has to be further developed and the cost reduced if recovery is to be economically viable. Stainless steels are found in very small quantities in MSW because they are worth removing from the waste stream by the established secondary materials industry. Virtually all solid lead recovery is from automobile storage batteries. Discrete copper parts can be separated by picking. Antimony found in lead can be removed. Nickel and chromium found in alloys of various types are potential targets for removal, as are other metals. The technology for tin recovery has been established, and this metal is being recovered presently.

Glass Recovery

Glass in the form of bottles and containers comprises about 10 percent by weight of MSW. It is estimated that 70 percent of this glass can be recovered and provide up to 30 percent of the industry's raw material requirement. Glass can be recovered by many techniques, primarily by screening after fracture in a shredder. It lends itself well to gravity separation, although care must be taken since its specific gravity is similar to that of aluminum. Glass also may be optically sorted, yielding clear and colored glass.

The main use of glass is as cullet to be added to the raw materials that make up the glass batch. In the past, primarily "home" cullet was used to promote melting and fining in the melting process. This cullet, which is produced in the glass plant, has the same composition and rheological properties as the formed articles. This is preferred to "foreign" cullet from other glass sources. Most recently, with the opportunity to use more cullet, changes in batching techniques were made in glass plants. These changes were calculated on the basis of the composition of the foreign cullet, and it was found that up to about 20 percent cullet could be added, a significant increase over the 10 percent previously used. There are some problems that must be eliminated involving seeds, cords and stones, defects that are caused by nondissolving refractory impurities or segregation of the glass in its molten state. Segregation causes separations, or cords, which

Table 3. Current status of resource recovery facilities.

Location	Process	Capacity (ton/day)	Year	Capital cost per daily ton ($1000)	Output
		In operation			
Braintree, Mass.	Waterwall incinerator	240	1971	10.4	Steam
Nashville, Tenn.	Waterwall incinerator	720	1974	25.7	Steam, ferrous
Saugus, Mass.	Waterwall incinerator	1200	1975	30.8	Steam, ferrous
E. Bridgewater, Mass.	Shredded fuel	600	1973	16.7	Fuel, ferrous
St. Louis, Mo.	Shredded fuel	650	1972	3.7	Fuel, ferrous
Baltimore, Md.*	Pyrolysis	1000	1975	16.0	Steam, ferrous
Charleston, W. Va.*	Pyrolysis	200		22.5	Gas, slag
Franklin, Ohio*	Materials recovery	150	1971	21.3	Fiber, ferrous, glass, nonferrous
		Under construction†			
Ames, Iowa	Shredded fuel	200	1975	27.5	Fuel, ferrous, glass, nonferrous
Bridgeport, Conn.	Shredded fuel	1600	1977	18.1	Fuel, ferrous, nonferrous, glass
Chicago, Ill.	Shredded fuel	1000	1976	16.0	Fuel, ferrous
Milwaukee, Wis.	Shredded fuel	1000	1976	17.0	Fuel, ferrous, paper
New Orleans, La.	Materials recovery	650	1976	8.7	Ferrous, glass, nonferrous, paper
San Diego, Calif.	Pyrolysis	200	1976	32.0	Oil, glass, ferrous, nonferrous
		Final design/planning			
New Britain, Conn.	Shredded fuel	1800	‡	12.2	Fuel, ferrous, nonferrous
Monroe Co., N.Y.	Shredded fuel	2000	‡	12.5	Fuel, ferrous, nonferrous
St. Louis, Mo.	Shredded fuel	8000	‡	8.8	Fuel, ferrous, nonferrous
Akron, Ohio	Waterwall incinerator	1000	‡	18.0	Steam, ferrous
Hempstead, N.Y.	Pulped fuel	2000	‡	27.5	Power, ferrous, glass, nonferrous

*Demonstration or test facilities operational between 1976 and 1980.

† Planned year of operation and costs are estimates.

‡Year of operation for these facilities is uncertain, but they are all expected to be

are visible when the glass cools down. Nearly all metals can cause color changes in glass; the most severe is iron, which causes the glass to turn green.

There has been an increasing public interest in separating glass; it is estimated that more than 2 billion bottles and jars have been reclaimed so far. Most of this glass, if separated, becomes cullet. There have been successful tests for the use of crushed glass as a road-building material with asphalt, or as clean fill. Glass has also been used as a fluxing material in the manufacture of bricks.

Plastics

Today petrochemical feed stock requires somewhat more than 3 percent of the crude oil used in the United States. Plastics fabricators are experiencing difficulty in obtaining supplies and are searching for substitute materials and new methods of reclaiming scrap. The growth rate in plastics production has increased annually by about 8.5 percent from the years 1950 1970, and in 1972 there were 24.2 billion pounds of plastic sold (*10*). It is estimated that plastics made up about 2 percent by weight of the MSW in 1973, amounting to about 3 million tons. With increased plastic use the quantities could rise significantly in the United States. (It approaches 8 percent in Japan at the present time.) From a practical viewpoint, none or very little is recycled as plastic, but some does go into shredded fuel and processes that generate energy. Plastics are high in heat value (10,000 to 16,000 Btu per pound). Plastics of the polyvinyl chloride and polyvinyl fluoride type may cause problems in incineration because of the halogen gas produced, which also may give rise to more rapid deterioration of incinerator linings. Increased quantities of plastics will cause a decrease in the bulk density of the MSW, giving rise to increased packing volume and more difficulty in transport and processing.

Of the two types of plastics that are currently manufactured, only thermoplastics may be reused. These make up 80 percent of the plastic in MSW and may be reworked by heat. They are, in decreasing order of quantity, polyethylene, polyvinyls, polystyrene, and polypropylene. The second type of plastic, thermosets, are unfusible and can not be remolded or reworked with the present technology.

Recovery methods for plastics are for the most part in a prepilot stage. Separation techniques of the thermoplastics depend on sink/float techniques presently. The products can be molded or used as fuel in pyrolysis or incineration. An area of current study is depolymerization to produce monomers, which can then be used as the building blocks for the polymers. The growth of the plastics industry is one that may affect the makeup of the waste stream considerably and result in increased recycling research.

Fuels

Increasing interest in the use of alternative fuels, including that derived from MSW, has been sparked by the oil shortage. If all the MSW were available in collected form in urban areas, it could supply about 7 percent of the fuel needs of the electric utilities (*11*). A summation of all the MSW fuel facilities existing, committed, planned, and under study would amount to the use of 44,000 tons of MSW per day and would generate about 1000 megawatts of power. This is less than 0.5 percent of the fossil fuel requirements of the electric utilities projected to 1980.

The pyrolysis process (*11*) gives rise to either fuel gas or fuel oil. The fuel gas produced has a low heat value of about 300 Btu per cubic foot and the estimated net thermal efficiency of the fuel preparation is about 66 percent. The gas can be varied in composition but primarily contains CO and H_2. The remaining 25 percent consists of CO_2, CH_4, C_2H_4, N_2, and H_2O. In tests (*11*), the gas when burned appeared to meet particulate emission standards and was low in both SO_2 and NO_x. If the heat value of the gas falls much below 300 Btu per cubic foot it would be difficult to introduce into existing systems because of the need to increase fuel pipe and duct sizes to enrich the flow. The gas can be upgraded by methanation or used to drive a gas turbine for power generation. Although gas yields are estimated at 24,000 standard cubic feet per ton of refuse, large-scale costs of production are not yet well defined because of the relative newness of the process.

The pyrolysis process can also be tailored to produce fuel oil. For every ton of MSW processed, about 1 barrel of fuel oil can be produced. This oil has about 35 percent less heating value than the standard No. 6 fuel oil, and tests indicate a heat value of about 10,500 Btu per pound. Pyrolytic oil has a higher moisture content, a low-

Table 4. Commodities recoverable from municipal solid waste, 1972 to 1990. [Source (*15*)]

Year	Ferrous metal (1000 tons)	Aluminum (1000 tons)	Glass (1000 tons)	Paper[a] (1000 tons)	Energy (10^{12} Btu)
1972	70	27	275	50	19
1975	285	51	275	300	61
1980	590	105	375	650	230
1985	1715	280	600	1200	486
1990	3135	510	850	2900	

[a]Paper reclaimed as energy reported in energy category.

Fig. 4. Increasing potential for materials recovery from MSW.

er *pH*, and higher viscosity than No. 6 fuel oil. Although early in its development stage, the oil shows some corrosion and storage problems. Its viscosity appears to be affected by temperature, water content, and degree of polymerization. The oil, with moisture dissolved in it, shows frothing and bubbles from steam evolution near the boiling point of water. It also exhibits non-Newtonian behavior, and its viscosity increases at low shear rates. Burning tests seem to have gone well with low SO_x emission. Although pyrolytic oil was reported (*11*) to blend well with No. 6 fuel oil, caution must be taken because of its insolubility. Its higher acidity has given rise to corrosion of mild steel and some stainless steels, and it appears to be as corrosive as acetic acid.

Solid fuels are the product of either the dry shredded or wet pulping processes (*4*). Depending on the preparation technique, it varies in heat content from 3500 to 8000 Btu per pound. Moisture content can vary from less than 2 percent for dry shredding to 50 percent for wet pulping. Depending on the preparation technique, ash content can vary from 5 to 20 percent. These ranges in values are to be expected because of the wide variation in processing; however, the operating parameters in any one process can be fixed so that the fuel is consistent and predictable. In all cases it is high in particulates, but its low sulfur content makes it attractive from an emission standpoint.

A process not previously described treats landfill as a gas-generating facility and by anaerobic digestion of MSW produces a gas primarily composed of methane and carbon dioxide. This gas has a heating value of approximately 600 Btu per cubic foot.

Observations and Conclusions

The building of resource recovery facilities to process the municipal waste stream has progressed at an increasing rate over the past 5 years. The current status of domestic processing facilities is shown in Table 3 (*12*). Also shown are the processes involved, the products, the estimated capital, costs, and the daily capacities. Energy recovery appears to be dominant, as would be expected at this time. In each of these processes some material is recovered, but the quantities are expected to be small because of the difficulty in product marketing. Five years ago it was felt that technology was the rate-controlling step for development of MSW recovery; although important, it now appears not to be the limiting factor. This is not meant to imply that all technical problems have been solved, but rather that there is enough confidence in the various technologies to design, build, and operate plants. There are technical problems still to be solved, for example, use of materials in corrosive and abrasive environments, grinding and classification, particle size and shape of the material to be processed, emission and ash, and structural materials and their availability. These are meant to be representative and not a complete listing. The plants that appear to have the least potential problems in operation are those that have had good operating experience in Europe, that is, waterwall incinerators. At this stage they seem to offer a higher level of confidence than pyrolysis and shredded fuel plants, but it is expected that this will change after more operating experience is gained.

The processes for recovery and the products recovered have been discussed in this article, primarily from a technical vantage point. However, in the area of municipal waste recovery there have been other dimensions to the problem, other than technical, that are very significant. The existing secondary materials industry has been developed to recover primarily paper and metals through a set of institutional arrangements that were created over the past 50 years. Recovery from the municipal waste stream presents a series of problems that are just being explored, and future roles of the participants may differ greatly from existing ones (*6*). For example, the municipality now generates and owns the refuse, and the final user may not be easily identified. Private industry has been involved in the building of many recovery installations, and questions of financing, ownership, and operation are being raised. Quantity guarantees and the quality of the refuse are other issues that keep surfacing. The areas of economic viability and problems with institutional overtones appear to be most significant and will determine, in the marketplace, the degree and level of recovery. Key institutional problems include regulation and laws concerning the environment, ownership and financing of facilities, and roles to be played by municipalities, states, the federal government, private industry, and markets for products.

Perhaps the most important problem is that of markets for derived products. Insufficient attention paid to the development of such markets may result in little or no revenues to offset the high costs of solid waste processing. There are also serious but solvable problems in effecting a working relationship between the municipality, the waste generator, and private industry, the probable builder and operator of the facility. In some cases, a city is large enough to play all roles or a region can be developed to generate, build, operate, own, and market products, but this will probably not be the rule in the next 5 years.

Any examination of potential future waste generation and recovery must be somewhat conjectural. It has to be based on life-style changes, population growth, and intent for recovery. The desire for recovery will most likely be affected by factors such as the economic viability of the processes, the problem of security of sources of materials on a national scale, breakthroughs in technology that can affect recovery yields and costs, and the role of government (municipal, state, and federal) in legislation. Legislation can affect the volume generated, shipping costs, financing and guarantees, emissions and residuals, and design of products for recycling, to name but a few. In Fig. 4, estimates are given for annual gross discards, per capita generation, and projections to 1990 for the level of resource recovery. These predictions were based on a study for the Environmental Protection Agency (*13*). While they appear as reasonable as any other estimates in the literature, they are based on a series of projections that can easily change. Figure 4 assumes no major federal intervention through resource recovery or source reduction incentive programs, and a continuation of historical growth rates for the economy in general. A more detailed commodity analysis is shown in Table 4 for the same time period with projected recovery through 1990. A distinction between projected recovery and potentially recoverable materials must be kept in mind in examining such an analysis. The potentially recoverable materials can, in some cases, be an order of magnitude greater than quantities actually reclaimed. Although the projected quantities increase with time, they still represent, in most cases, less than 1 percent of the total U.S. demand for iron, aluminum, and energy. However, when compared to U.S. mine production these numbers take on a new significance. For example, by 1990 MSW can contribute iron equal to 6 percent of domestic mine production and more than 1½ times as much aluminum as the domestic mine production. It is estimated that at present prices the value of the scrap in MSW approaches $1.5 billion in 1975. Table 2 shows the elements in the magnetic portion of incinerator residue which may have potential for recovery. It seems possible that as more plants become operational, there may be a tendency to reexamine the processed MSW "culm piles" for

additional recovery, as is presently being done in the copper industry. One can envision that portions of these unrecovered materials will be shipped to processors throughout the country who have developed expertise for specific commodities, and that interindustry waste processing centers will develop. In addition, new complementary processes are being developed around the environmental park concept. Processing is located at sites where sewage sludge and MSW are used to produce energy, heat from waste water is reclaimed for mariculture and silviculture, and surroundings are developed for recreational use. There are other innovative approaches involving the combination of MSW with other waste materials such as agricultural or industrial wastes and the combination of MSW with high sulfur coal to produce metals and steam. Although offering potential for the future, techniques such as these have not been adequately developed to analyze fully.

This is an exciting period; we are looking at a total system brought on by societal needs, and trying to convert what has been a liability into an asset. Although the recovery of energy and material quantities may not be a substantive part of the total U.S. materials needs, by recovering these commodities we are helping to solve the problems of municipalities and to add to our energy and materials supply.

References and Notes

1. Conversion factors for the nonmetric units used in this article are as follows: 1 pound = 0.45 kg, 1 ton = 0.907 metric ton, 1 Btu = 1.055×10^3 joules, 1 cubic foot = 0.028 m^3, and 1 barrel = 0.15 m^3.
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3. S. I. Blum, *National Materials Policy*, proceedings of a joint meeting of the National Academy of Sciences–National Academy of Engineering, October 1973 (National Academy of Sciences, Washington, D.C., 1974), pp. 107–111.
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The Economics of Resource Recovery from Municipal Solid Waste

James G. Abert, Harvey Alter, and J. Frank Bernheisel

Environmental concern has drawn attention to means for recovering material and energy resources from urban solid waste, particularly from the household portion (*1*). Recently, federal support has been given for this purpose (*2*). The public viewpoint is that the metal, glass, and other materials found in ordinary refuse are resources to be saved, preserved, and recovered rather than discarded. Recovery, outside of separation by the householder, depends on the availability of suitable separation technology operated at a reasonable cost to the community.

Unfortunately, progress in affecting the installation of recovery facilities to meet the needs of communities has been slow. Much of the work done has been beset with technical, and, more often, economic difficulties. However, the rising cost of traditional and environmentally acceptable means of disposal may allow new systems to become economically competitive. New systems hold promise. The Environmental Protection Agency in late 1972 announced four grants, under Section 208 of the Resource Recovery Act of 1970 (*3, 4*), for the construction of resource recovery plants of at least 200 tons per day capacity to demonstrate new technology. Many unit operations familiar in chemical, mechanical, and minerals processing engineering practice can be, and already have been, applied to refuse processing and resource recovery (*5*). Their final adoption will depend on their costs to the community being competitive with traditional methods of disposal, such as sanitary landfilling or incineration.

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Raw Materials

Before considering the costs of resource recovery, one must examine what there is to recover—that is, what is likely to be in the solid waste stream. This article is focused on the household portion of the urban solid waste.

The results of several analyses (*6*) of the composition of household refuse by weight resulted in the values given in Table 1. Unfortunately, there is no such thing as an average refuse composition. The composition varies from city to city—probably geographically and no doubt seasonally and temporally, from year to year and on shorter time scales, all making definitive analysis difficult. There are, however, some general trends in composition that can serve as design input for technical and economic analysis. First, some nominal composition figures can be computed, using one's judgment, from the available data (*7*). Second, it is apparent that municipalities with a "high" refuse assay have an economic advantage in implementing recovery facilities. A high assay means that the content of the valuable, nonferrous metals must be about 1 percent.

Recovery potential falls into two basic groups of materials (see Table 1). The first group of items is labeled "mechanical recovery" and refers to that portion of the refuse stream which is available for essentially mechanical extraction and for reuse as a relatively pure raw material. The sec-

ond group includes what are primarily organic materials, which, because of their physical characteristics, can only be recovered through conversion. Organic materials are generally suitable for some sort of derived product, such as compost, or a manufactured product, such as fiberboard building material (*3, 5, 8*), or for chemical or biological conversion to a source of energy—either directly, by burning, or indirectly, by converting to a storable fuel (*9*).

Paper is included in both categories. Some is recoverable as a material, but most is not. This is due, in large part, to composite packaging (that is, paper laminated or otherwise attached to plastic or metal) and to the collection process. When mixed with other refuse, paper becomes contaminated with dirt, grease, and other materials that are not acceptable inputs to high-speed paper-making processes and that are difficult to remove, even with special processing (*10*). However, it is probable that some small fraction of paper, most likely bundled newsprint and corrugated board, can be efficiently separated from mixed refuse by hand in a form acceptable for some reuses.

Therefore, based on the composition of the refuse stream, recovery is essentially a two-phase process: first, materials recovery (glass, metals, and some paper); and second, recovery of the organic portion and reuse through conversion, probably as a source of energy.

One scheme for recovering materials and energy from solid waste is shown in Fig. 1. "Front end" refers to materials recovery with disposal of the organic portion by conventional means—for example, by landfill or incineration. This is a suboptimal system because it is incomplete. "Back end" refers to the recovery of the organic portion and its reuse as fuel or as raw material for a product (*11*).

A flow sheet for a front end recovery process proposed by the National Center for Resource Recovery (*12*) is shown in Fig. 2. The bases for choosing this type of materials recovery plant and details of the various unit operations have been described (*13*), as have other technically feasible processes (*5*). The system shown in Fig. 2 would recover five fractions: bundled paper, ferrous metals, glass, aluminum, and a mixture of other nonferrous metals (including nonmagnetic stainless steel). It would leave as residue the organic fraction (for disposal or recovery) and a small inert fraction consisting of bone, rubber, heavy plastics, grit, sludges, and dust from the processing (for disposal by landfill). An important aspect of "beginning" with the front end system is that the economic analysis does not have to include the normally high cost of marketing new products. This cost would be necessary for many back end systems, such as those which produce new kinds of building materials. Further, the economic viability of the front end system is not hampered by the high capital cost of constructing refuse-burning heat exchangers for energy recovery.

Cost Estimates

The first step in the economic analysis of resource recovery is to determine the capital costs and operating costs of the technology to be installed. A plant processing 500 tons of solid waste per day (like that in Fig. 2, which would serve most of the needs of a community of about 200,000) has been estimated in some detail to have a capital cost of $2.4 million, exclusive of land (*13*). These costs are explained in Table 2. Operating costs have been estimated (*13*), and are summarized in Table 3, on the basis of a debt-to-equity ratio of 2 : 3. This would apply to the situation in which a private entrepreneur constructs and operates a plant of this kind as a business venture. Public ownership is also possible.

The costs of back end processing facilities are more difficult to obtain or analyze because the technology is generally new and often proprietary. However, it seems that the most efficient and inexpensive (in terms of capital) means of extracting energy from the organic fraction would be to use it as a supplementary fuel in existing coal-fired boilers for generating electricity, as is now being done in St. Louis (*14*). The cost of modifying the plant and any increase in the cost of operation of such a utility boiler may be paid for by the value of the organic fraction as a fuel.

General Economic Considerations

A great deal has been written about the economics of environmental quality, with discussions of internalization of costs, redistribution of income, costs and benefits to society, and so forth (*15*). It is not our intent to review or enter into these arguments here. Rather, we seek to determine the cost to a community of adding resource recovery to its solid waste management system. Put another way, we apply the "indifference principle"; the indifferent community is one for which the added resource recovery would cost the same as its present

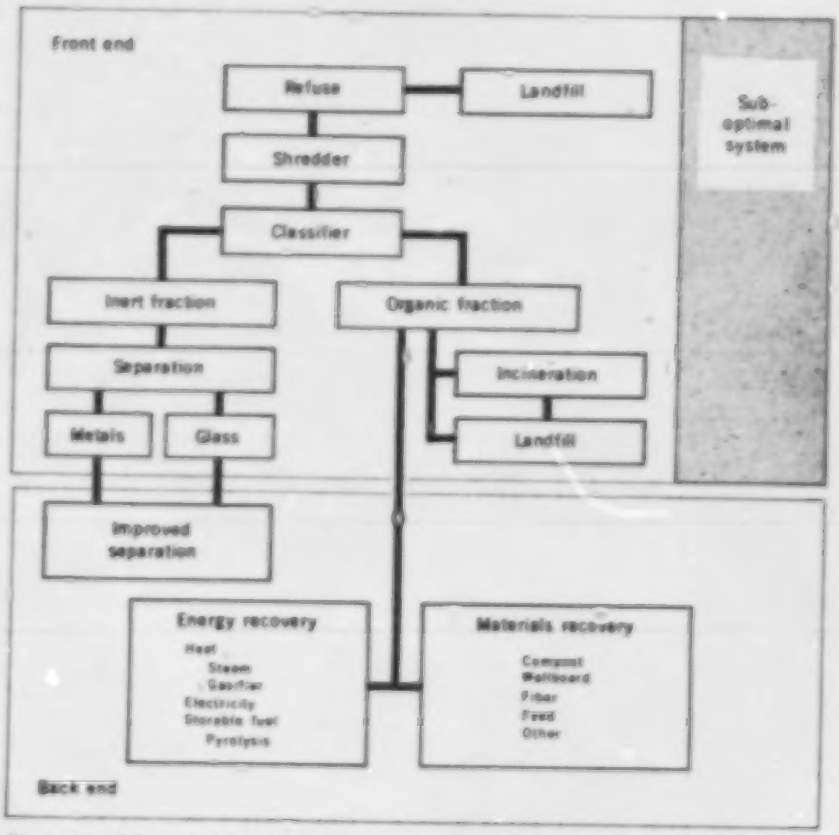

Fig. 1. A modular approach to resource recovery. Front end refers to materials recovery. Back end refers to direct utilization, or conversion, of the organic portion of the waste.

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solid waste management practice. In this day of environmental concern, the indifferent community may also be one to which the extra cost of having resource recovery is acceptable as a means of participating in materials conservation programs.

A cost center concept is the basis for evaluating the recovery facility. Refuse is accepted for processing for a fee paid to the facility, and unrecovered by-products and residues are disposed of for a fee paid by the facility. It is assumed that the facility is privately owned and is operated at a profit. If the facility is economically feasible under private ownership, it may be less expensive to implement under public ownership because a public body does not require a profit and can often borrow capital at lower interest rates.

For purposes of analysis, the characteristics of a prototype facility are assumed to be the same as those described in Tables 2, 3, and 4, with a profit before taxes or return on an equity of 15 percent, which is assumed to be the minimum that would attract private capital (considering present interest rates on certificates of deposit and other relatively safe, often tax-free, investments).

The fraction of incoming refuse recovered as salable material (Table 4) is determined by the expected efficiency of an operating plant and by the average expected composition of the incoming refuse (*13*).

Table 1. Expected ranges in mixed municipal refuse composition. [Source: (*6*, p. 5)]

Component	Composition (% of dry weight)*		
	Range	Nominal	
Metallics	7 to 10	9.0	Mechanical recovery
Ferrous	6 to 8	7.5	
Nonferrous	1 to 2	1.5	
Glass	6 to 12	9.0	
Paper	37 to 60	55.0	Conversion recovery
Newsprint	7 to 15	12.0	
Cardboard	4 to 18	11.0	
Other	26 to 37	32.0	
Food	12 to 18	14.0	
Yard	4 to 10	5.0	
Wood	1 to 4	4.0	
Plastic	1 to 3	1.0	
Miscellaneous	< 5	3.0	

* Moisture content: range, 20 to 40 percent, nominal, 30 percent.

The Operating Statement

Under the cost center concept, a prototypical operating statement can be used in economic analysis. Such a statement must include entries for all operating expenses and revenues for the stated equity, as well as target return on this equity. An example of an operating statement is shown in Fig. 3.

Net operating income provides the return on equity previously discussed. Total operating expenses are the sum of annual

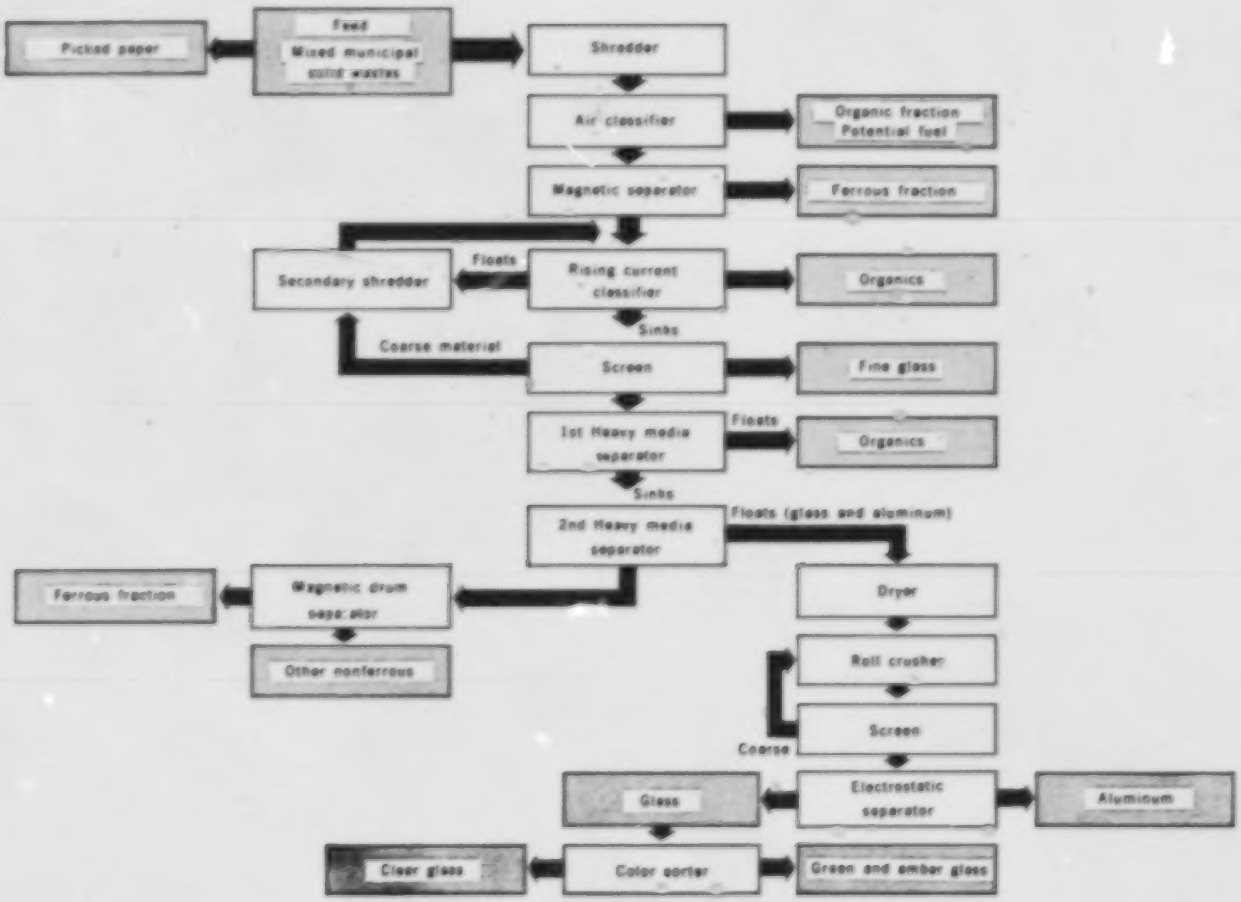

Fig. 2. Processing scheme for separating materials from mixed refuse.

operating costs (derived as shown in Table 3) and waste product costs, which are costs resulting from the disposal of unrecovered material. By-product revenues are net proceeds from the sale of recovered fractions (*16*). The dumping revenue is a per-ton fee paid by the community or by private haulers to the facility for disposing of the refuse.

The by-product revenues are based on the expected annual recovery rate for each potentially recoverable resource and on the anticipated selling price for each material. The expected recovery of each material is listed in Table 4; the engineering estimates made to arrive at these figures have been described elsewhere (*13*). The expected selling price for each material is a judgment based on examination of analogous scrap prices quoted in trade publications (*17*), conversations with potential buyers, and freight charges over a likely distance.

The following net prices were arrived at: ferrous metals, at $15 per ton (based on a No. 2 scrap bundle price of about $35 per ton, delivered to the steel mill and allowing $20 per ton for transportation); glass, at $7 per ton (based on 12 percent of the glass output being sorted as flint at $12 per ton and the remainder being color-mixed at $8 per ton and allowing only for local transportation costs); paper, at $10 per ton (mostly No. 1 news, a standard paper stock—price estimates vary greatly with area of the country); aluminum, $200 per ton net (quote from an aluminum producer); and nonferrous metals, excluding aluminum, $120 per ton (based on prices paid per ton for metal contained in some nonferrous concentrates from automobile-shredding operations). The likely by-product revenues for the operating statement, calculated on these estimates, are listed in Fig. 3, with entries for all the costs and revenues established so far (*18*).

Figure 3 illustrates the oft-heard argument, and a correct one, that the by-product revenues from resource recovery cannot support the cost of separation. By-product revenues are listed as $562,000, falling short of expenses ($819,000) by $1.65 per ton of input. These arguments are incomplete, however, because they do not take into account other entries to the operating statement that must be added in order to determine the economics of such a facility.

First, the prototype plant discussed here processes 500 tons per day, 6 days a week. Of this input, 19 percent is recovered, and hence does not generate a disposal cost for the facility. In order to balance the operating statement and to determine the point of indifference mentioned earlier, the credit for the dump revenues and the debit for the waste product disposal costs must be such that the net operating income equals the target rate of return, $216,000 per year. This may be stated:

$$156{,}000(DR) - 126{,}360(WPC) = \$473{,}000 \quad (1)$$

The $473,000 are operating costs plus profit, minus by-product revenues. Dump revenues (*DR*) and waste product costs (*WPC*) are expressed in dollars per ton.

The equation can be solved for both *DR* and *WPC* if a relation can be established between the two unknowns. A plausible one is

$$0.75(DR) = (WPC) \quad (2)$$

In other words, there is a 25 percent discount in the cost of disposing of the waste products after processing (shredding and removing of the inert material).

It is believed that this discount can be justified if the processed refuse is disposed of in a landfill, particularly in areas where land is expensive and dirt to cover the refuse is scarce. With the same mechanical effort, shredded refuse can be made more compact than unshredded refuse; it therefore requires less land for disposal. In addition, there is substantial evidence that shredded refuse does not need daily earth cover and thereby saves on clean fill, often a scarce and costly material (*19*). Shredded refuse without cover requires fewer earth-moving machines and compactors for landfilling than does unprocessed refuse. The lower requirement saves capital investment and daily operating costs. Finally, because shredded refuse as fill stabilizes more rapidly, compared to unshredded material, the filled land is available sooner for capital improvement. This is often an income-producing item for the municipality. The potential savings in each of these various categories have been estimated (*13, 19*) and are summarized in Table 5. In the case of landfill without daily cover, Eq. 2 seems justified, if not conservative.

It is more difficult to make a similar case for Eq. 2 when the unrecovered fraction is disposed of by incineration. Although the burning of shredded wastes, such as bark and bagasse, has been practiced for years, it has only been in the last 4 years or so that municipal incinerators operating on shredded refuse have been put into operation. One such plant is in the city of Hamilton, Ontario. In the Hamilton plant, there are several design innovations aimed at reducing costs of incineration. Among these are conveyor belts, rather than overhead cranes, for handling refuse. Also, because of suspension burning, the combustion chamber is smaller than a conventional incinerator of the same capacity. Finally, there is no need for water quench of the ash; it is cooled in suspension by the air flow. Because the Hamilton plant is new, data on actual costs are not yet available. However, it is likely that the oper-

Table 2. Summary of capital costs. [Source: (*13*, pp. 9-1–9-53)]

Item	Cost ($)
Building	173,000
Electrical equipment	192,300
Water and sewage	124,000
Auxiliary equipment	119,830
Processing equipment	914,300
Subtotal	1,523,430
Architecture and engineering (10%)	152,343
General contracting and architect-engineer field supervision costs (23%)	350,389
Contingency (19%)	289,452
Working capital	100,000
Total	2,415,614

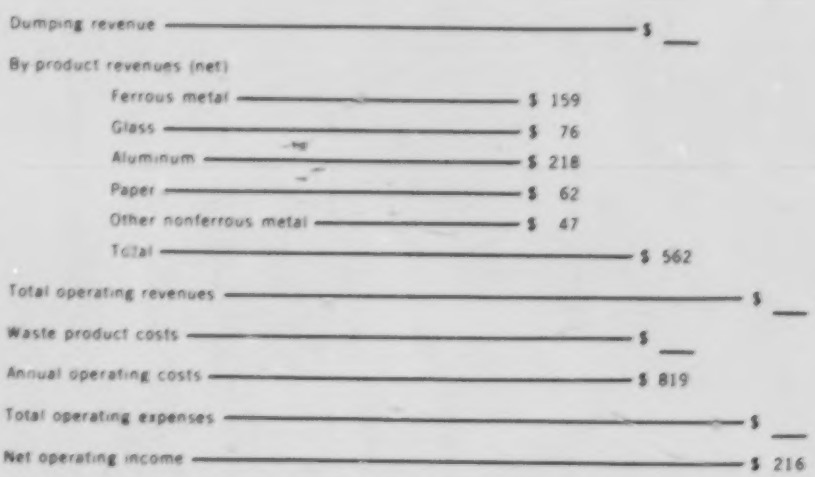
Dumping revenue — $ —
By product revenues (net)
Ferrous metal — $ 159
Glass — $ 76
Aluminum — $ 218
Paper — $ 62
Other nonferrous metal — $ 47
Total — $ 562
Total operating revenues — $ —
Waste product costs — $ —
Annual operating costs — $ 819
Total operating expenses — $ —
Net operating income — $ 216

Fig. 3. Prototypical operating statement showing the format and fixed entries, of a resource recovery facility (annual rates in thousands of dollars; equity, $1.44 million; return on investment, 15 percent).

ating costs for the complete facility are slightly less than those for conventional incinerators using unshredded feedstock. In time, the coefficient in Eq. 2 will be determined for incineration of shredded refuse. Until then, 0.75 will serve as an estimate.

When Eqs. 1 and 2 are solved, the indifferent community is one where the cost of disposing of unprocessed raw refuse (DR) is $7.72 per ton and the cost of disposing of the shredded refuse (WPC) is $5.79 per ton. A completed operating statement is shown in Fig. 4.

It is important to point out the three sources of revenue for the front end recovery facility. First, it can sell the recovered materials; second, it does not have to dispose of the recovered materials; third, it can charge a fee for the service of preparing refuse for the landfill. (In the example here, the facility can charge 25 percent of the raw refuse disposal cost, or $1.93 per ton for this service.)

The Indifferent Community

A resource recovery facility of the sort described would be economically feasible when the cost of operating the landfill, or incinerating raw, unprocessed refuse, is the $7.72 per ton calculated above and when disposing of the shredded, unrecovered residue is, accordingly, $5.79 per ton. If these figures are exact, then the community is indifferent; resource recovery costs no more or less than present disposal practices. If the community is paying, or expects to have to pay, more than this in the near future, obviously resource recovery would save it money. If current (or projected) costs are less, then a front end resource recovery system would be an add-on incremental cost.

This last circumstance warrants further discussion.

If the community is paying less than $7.72 per ton to dispose of its refuse, it is not indifferent, because recovery would cost more than the community would otherwise have to pay. The community would have to decide the worth of resource recovery in light of other demands such as those for schools, medical care, and housing. However, an example may place this new demand in perspective. A family of four generates approximately 2 tons of refuse per year. An incremental cost of $2 per ton could be incurred as a result of a decision to construct and operate a front end resource recovery system. The $2 per ton figure is not exact, but is the likely size of the increment. The point is that, on a per-family basis, this is not a very large incremental cost.

Dumping revenue	
(156,000 tons per year, at $ 7.72 per ton)	$ 1,204
By-product revenues (net)	
Ferrous metal	$ 159
Glass	$ 76
Aluminum	$ 218
Paper	$ 62
Other nonferrous metal	$ 47
Total	$ 562
Total operating revenues	$ 1,766
Waste product costs	
(126,360 tons per year, at $5.79 per ton)	$ 733
Annual operating expenses	$ 819
Total operating expenses	$ 1,552
Net operating income	$ 216

Fig. 4. Prototypical operating statement, for materials recovery alone, of a resource recovery facility (annual rates in thousands of dollars).

Dumping revenue	
(156,000 tons per year, at $3.96 per ton)	$ 618
By-product revenues (net)	
Ferrous metal	$ 159
Glass	$ 76
Aluminum	$ 218
Paper	$ 62
Other nonferrous metal	$ 47
Total	$ 562
Total operating revenues	$ 1,180
Waste product costs	
(24,960 tons per year, at $5.79 per ton)	$ 145
Annual operating costs	$ 819
Total operating expenses	$ 964
Net operating income	$ 216

Fig. 5. Prototypical operating statement, for materials and heat recovery, of a resource recovery facility (annual rates in thousands of dollars).

Utilization of the Organic Fraction

Figure 4 shows that 47 percent of the total operating expenses of the facility is the so-called waste product disposal cost; for the most part, this unrecovered residue is organic and, therefore, combustible. A more beneficial course would be to recover this residue for use as energy.

Consider the cost of burning the combustible portion of household refuse in an electric utility boiler, along with coal, to generate electricity. In order to prepare an operating statement for a facility in which the organic fraction is so utilized, certain assumptions must be made about the amount of combustible residue, the costs of utilizing this fuel, and the costs of disposing of the wastes.

Not all of the residue can be burned. In the example represented by Fig. 4, it is estimated that approximately 16 percent of the residue (24,960 tons per year) will not be combustible and, therefore, must be disposed of in a landfill. Assume also that the cost of disposing of the residue is the same as in the case of Fig. 4—that is, $5.79 per ton. Finally, assume that the value of the organic fraction as a fuel exactly offsets the cost to an electric utility for capital modifications necessary to accept and burn it (judged to be about $1 million) and any added operating costs, such as for ash handling, air pollution control, added maintenance, and so forth (*14*, *20*). In other words, assume that the organic fuel fraction is delivered to the utility boiler at no

net cost to the recovery facility. Under these assumptions, the prototypical operating statement of Fig. 4 is modified to Fig. 5, and the dump fee is reduced to $3.96 per ton. This illustrates the large economic advantage of such energy recovery. Disposal costs are obviously reduced. The indifferent community of the previous example, whose disposal costs for raw, unprocessed waste were $7.72 per ton, now saves $3.76 per ton on its disposal system.

The indifferent municipality is replaced by one whose alternative disposal costs are $3.45 per ton (*21*). This lower figure greatly expands the number of communities in which resource recovery is economically viable, provided that the community has an electric utility which can utilize the organic fraction and that all other assumptions hold.

Public Ownership

The same type of operating statement analysis can be used in cases where the facility would be publicly owned. The net operating income figure of $216,000 is not required, since most public bodies seek only to recover costs. In addition, the interest and depreciation entries must be modified for public financing. Also, the real estate tax entry is dropped. However, the community now loses this revenue, so, strictly speaking, in a total calculation of costs and benefits, real estate tax should be included as a cost (revenue decrease). Public financing may be through a revenue bond or general obligation bond (*22*). A 6 percent interest, 10-year bond with a level annual payment is assumed to supply the total capital requirement of $2,415,614 for the facility (Table 2). This results in a reduction of the community's disposal cost to $5.78 per ton for the materials recovery case and $2.09 per ton for materials plus energy recovery. Thus, resource recovery is possible for greater numbers of communities when some form of public financing is used.

Table 3. Annual operating costs of a plant processing 500 tons per day, 6 days per week. Basis: 40 percent of capitalization debt; 60 percent equity. [Source: (*13*, pp. 9-1–9-53)]

Operating costs	Expenditure ($)
Variable	
Labor*	258,425
Maintenance materials	74,327
Utilities	64,800
Total variable	397,552
Fixed	
Depreciation†	306,530
Real estate taxes and insurance‡	39,429
Interest§	75,000
Total fixed	420,959
Total net	818,511

*Labor costs are based on paying time-and-a-half for the sixth day. †Depreciation is straight line based on 20 years for buildings and 7 years for equipment. ‡Land assumed to be provided rent-free by the municipality. §Based on borrowing 40 percent of capital cost at 8 percent simple interest, paid quarterly for 20 years on building and 10 years on equipment. Interest shown for the first year of operation.

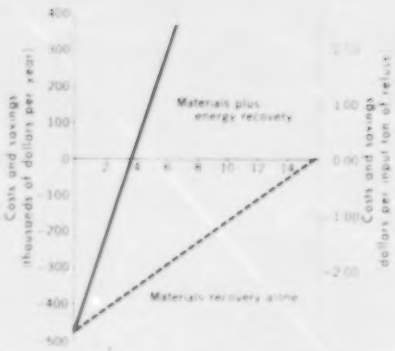
Costs and savings (thousands of dollars per year)
Materials plus energy recovery
Materials recovery alone
Costs and savings (dollars per input ton of refuse)

Fig. 6. Graph of incremental costs and savings for implementing resource recovery. No discount in the cost of waste disposal is assumed.

Incremental Costs and Savings

The potential incremental costs or savings per ton for private resource recovery facilities are plotted in Fig. 6. The abscissa shows the disposal cost in dollars per ton. Both the materials recovery case and the materials plus energy recovery case are shown. In this case, no added value for the shredding process is assumed (in other words, $DR = WPC$). Hence, Fig. 6 represents a "worst possible case"—that is, the case in which the cost of disposing of shredded refuse is the same as the cost of disposing of raw, unprocessed refuse.

For the materials recovery case, the graph illustrates that, unless disposal costs are high (greater than $15.90 per ton), there is an incremental cost associated with resource recovery. For the community discussed previously, with a $7.72-per-ton disposal cost, the incremental cost is $240,000 per year, or $1.54 per ton. However, the line for materials plus energy recovery crosses the abscissa from cost to saving, indicating the indifferent community, at a disposal cost of $3.60 per ton. If current or near-term projected costs (say the average for the next 5 to 10 years) are above this value, there is a savings to be realized by installing materials and energy recovery. Figure 6 can be used to estimate the course a community might follow in planning a solid waste management system.

Summary

A prototypical operating statement similar to that used by business firms has been shown to be a useful decision-making tool for a community choosing a solid waste management system. When applied to resource recovery, it highlights the economics of recovery and the values of the input parameters necessary to achieve economic viability, whether in the case of public or private ownership (*23*).

In most communities, refuse processing to recover material resources must be based on more than one source of revenue. In addition to the revenues from the sale of by-products, there must be revenues from processing the incoming refuse and from a user, or dump, fee. In the first case discussed, that of materials recovery by a front end system, resource recovery is shown to be economically feasible for those communities in which the present cost of disposal is relatively high. The indifferent community was one having a current cost of $7.72 per ton; more accurately, this would be the cost for the near-term future. It is not necessary that current costs be used, since many communities are merely "dumping" their refuse. The indifference decision should be based on the cost of an environmentally sound alternative.

Energy recovery from municipal solid waste can increase the number of communities in which resource recovery will be an economic adjunct to a solid waste management system. The analysis presented here

Table 4. Characteristics of prototype facility: size, 500 tons per day (156,000 tons per year input); capital cost, $2.4 million (exclusive of land); debt, $0.96 million; target return, 15 percent of equity ($216,000 per year).

Material	Weight recovered (%)
Ferrous metal	6.80
Glass	7.00
Aluminum	0.70
Paper	4.00
Other nonferrous metal	0.25
Total	18.75

Table 5. Potential savings, by cost category, resulting from the use of milled refuse.

Cost category	Saving (%)
Land	62
Capital improvement	Varies
Equipment	42
Operating	42
Materials	11

70

was based on the assumption that the value of the fuel recovered exactly offset the additional capital and operating costs of the utility which burns it. There could be costs above and beyond this; similarly, there could be a saving by taking into account the economic value of the organic fraction as fuel. However, it is believed that the assumption under which the materials-plus-energy case was analyzed seems to be realistic at this time.

References and Notes

1. Urban solid waste refers to all material collected in a community and consists of portions from households and commercial and industrial establishments, as well as construction and demolition rubble.
2. Resource Recovery Act of 1970, Public Law 91-512 (26 October 1970). Also S. 498, an extension of that act, passed 26 January 1973.
3. The awardees of Section 208 grants and the prime contractors or processes to be installed are State of Delaware: Hercules, Inc., Baltimore; Landgard pyrolysis: Monsanto Enviro-Chem Systems, Inc., Lowell, Mass.; Bureau of Mines Incinerator Residue, San Diego County, Calif.: Garrett Research and Development Company, Inc. For a description of the processes, see (*4*).
4. *Resource Recovery Catalogue of Processes*, prepared by Midwest Research Institute for Council on Environmental Quality (Council on Environmental Quality, Washington, D.C., February 1973).
5. J. G. Abert and M. J. Zusman, *Am. Inst. Chem. Eng. J.* **18**, 1029 (1972).
6. N. L. Drobny, H. E. Hull, R. F. Testin, *Recovery and Utilization of Municipal Solid Waste* (Publ. No. Sw 10c, Environmental Protection Agency, Solid Waste Management Office, Washington, D.C., 1971). The authors cite several sources of data.
7. The judgment exercised in developing nominal figures for discussion is stressed. In contrast, if a specific resource recovery plant is to be built, exact numbers must be obtained for that community. One method of doing this is described by F. R. Kaiser, C. Zimmer, D. Kasner, in *Proceedings of the National Incinerator Conference* (American Society of Mechanical Engineers, New York, 1970), pp. 25–31.
8. *A Study to Identify Opportunities for Increased Solid Waste Utilization*, report to National Association of Secondary Materials Industries, Inc., (Battelle Columbus Laboratories, Columbus, Ohio, 1972).
9. Storable fuel may be created from waste by several methods. Pyrolysis and anaerobic digestion processes are described in (*4*).
10. See, for example, J. F. Laundrie and J. H. Klangress, *Pap. Trade J.* **157** (No. 16), 34 (1973).
11. Many wastes do not have a use or have a very low economic use and, therefore, are not suitable for recovery. Hence, there will always be a need for some kind of landfill as an ultimate disposal method.
12. R. L. Lesher, *Environ. Sci. Tech.* **6**, 1078 (1972).
13. *Materials Recovery System, Engineering Feasibility Study* (National Center for Resource Recovery, Washington, D.C., 1972).
14. D. L. Klumb, *Solid Waste Disposal Seminar, Proceedings* (Union Electric Company, St. Louis, Mo., 1972).
15. For a recent discussion, see J. D. Headley, *J. Environ. Qual.* **1**, 377 (1972).
16. We do not intend to discuss the availability of markets and similar topics. These are covered adequately elsewhere—for example, in testimony before the Joint Economic Committee, Subcommittee on Fiscal Policy, *The Economics of Recycling Waste Materials* (92nd Congr., 1st sess., 1971). It is obvious that recovered materials will have to be sold according to specifications, like any other commodity. It is our experience that, under such conditions, buyers can be found when there is, or is to be, an assured source of reasonable tonnages of appropriately processed products.
17. See, for example, publications such as *Iron Age*, *Waste Product Journal*, and *Official Board Markets*.
18. Perhaps the only other material thought to be recoverable is plastics, for which no revenue is shown here. Although some plastics can be recycled if separated and cleaned, at present there are no efficient means of separating them from mixed municipal refuse in a sufficiently clean form for reuse in new products. It appears that the best use for plastic waste is as fuel. Some plastics have a high heat of combustion: that of polyethylene, for example, is 46×10^6 joules per kilogram [J. Brandrup and E. H. Immergut, *Polymer Handbook* (Wiley-Interscience, New York, 1966), p. VI-44].
19. J. Reinhardt, "A report on the demonstration of the Gondard grinding mill for pulverizing refuse and landfilling milled refuse without daily cover," final report to the Department of Health, Education, and Welfare, grant 5 001 UI 00004, undated.
20. R. A. Lowe [*Energy Recovery from Waste* (Publ. No. SW-36d.ii, Environmental Protection Agency, Washington, D.C., 1973), p. 13] states that solid waste as a fuel contains 0.1 percent sulfur and has a fuel value of about 11×10^6 joules per kilogram. Our own experimental studies (unpublished) indicated that, when air classified, the waste has a fuel value of about 19×10^6 joules per kilogram, dry weight basis. Therefore, at about 25 percent moisture, as received, and sold for $0.40 per 10^6 joules, the processed waste would be worth in excess of $5 per metric ton as a fuel.
21. To identify the indifferent community, Eqs. 1 and 2 must be restated. In Eq. 1, the waste product tonnage for materials plus energy recovery, 24,960 tons, is substituted for 126,360 tons of the materials recovery alone. Equation 2 remains the same. The result is:

$$156{,}000(DR) - 24{,}960(WPC) = 473{,}000 \quad (1)$$

$$0.75(DR) = (WPC) \quad (2)$$

The solution is DR = $3.45 per ton and WPC = $2.59 per ton.
22. The Pollution Control Bond is a form of the tax-free Industrial Development Bond, first sanctioned by the Internal Revenue Service in 1957. These bonds are issued by local governments to buy or build equipment and plants that are then leased to private corporations. This kind of financing resulted in a significant loss in tax revenue; as a type of tax reform, Congress passed in 1968 the Industrial Revenue Bond Act, which stipulates that no individual offering could be larger than $5 million. However, an exception was made for industrial revenue issues that were intended to finance pollution control equipment. There is no limit on the size of these issues. Early beneficiaries of this exemption were corporations installing air and water pollution facilities. In April 1970, the Internal Revenue Service approved tax-exempt bonds for solid waste recyling facilities. To qualify, the processed material must be of no value to the producer; that is, it cannot be used or sold by the producer at the location of processing or at the time the bonds are issued. In addition, 65 percent of the input must fit this definition. A broad interpretation appears to have been given to the term "solid waste facility." According to the Internal Revenue Service, solid waste facility means any property used for the collection, storage, treatment, utilization, and processing of solid waste that results in the reconstitution or final disposal of such waste [sec. 103(C) 4 (E), U.S. Internal Revenue Code].
23. There have been, of course, recent dynamic changes in the nation's price structure. Building and equipment, as well as labor, costs have increased. However, secondary materials prices have risen as well. Therefore, an updating of the figures given here would be in order before any final decision to enter into resource recovery is made. Nevertheless, the method of analysis and, in general, the conclusions of this article are valid over a broad range of price structures.

Courtesy Bureau of Mines, U.S. Department of Interior, Washington, D.C. →

Perspectives on Needs and Supplies of Resources

Limits to Exploitation of Nonrenewable Resources

Earl Cook

Nonrenewable resources consist of geochemical concentrations of naturally occurring elements and compounds that can or may be exploited at a profit. The concentrations that are at present exploitable at a profit range from slightly more than twice to several thousand times the average crustal abundance of the desired element (Table 1). Rates of concentration into ore bodies or oil pools appear to be slow compared to the pace of human history. Moreover, the formation of deposits of ores and mineral fuels appears to require unusual to extraordinary geologic conditions; consequently, such deposits are unevenly distributed in space and time, and they commonly occupy very small portions of the lithic prisms in which they are found.

Almost 70 percent of proved crude-oil reserves are in the Middle East, and five countries produce more than 65 percent of the world's copper. These nonuniform distributions are real and do not merely reflect differences in exploration effort. Many of the most common ore deposits appear genetically and spatially related to the boundaries of crustal plates (*1*). Other ore deposits not associated with crustal-plate margins may be localized by uplift of the crust over thermal plumes (*2*). Petroleum as well as metallogenic provinces exist, and the world's coal deposits are strikingly concentrated in the temperate belt of the Northern Hemisphere.

Not only are geologic resources distributed unevenly over the surface of the globe, they are concentrated in the outermost part of the earth's continental crust. Mechanisms that concentrate chemical elements operate most effectively on and near the earth's surface: weathering, erosion, sorting during transport, groundwater leaching, and supergene enrichment are effective only in the upper few hundred meters of the continents. Hot metal-bearing solutions encounter the precipitating effect of colder meteoric waters and find relatively high permeability only in the upper few thousand meters of the crust. Oil and gas formation, migration, and entrapment take place within the thin and discontinuous sedimentary skin of the continents. There is a hoary myth among old prospectors that ore bodies widen and get richer downward. In fact, they generally do just the opposite. The rich gold and silver deposits of the American cordillera are notorious for bottoming at depths of a few tens to a thousand meters. The Comstock Lode and the several ore bodies at Guanajuato (*3*) are excellent examples. The mineral-fuel analog is the transition zone in a reservoir rock between crude oil and water, a zone commonly only a meter or two thick; the world's greatest oil well, Cerro Azul No. 4 in Mexico, after producing more than 50 million barrels of oil, suddenly produced only salt water.

The limited nature of individual deposits, the difficulty of seeing through rock, and the history of many mining districts and oil fields have led to many forecasts of depletion and exhaustion. But, as old deposits have become exhausted and new ones have become harder to find, world mineral and fossil-fuel production paradoxically has continued to increase. There is a wide difference of opinion now on the question of limits to the exploitation of nonrenewable resources.

Three Kinds of Limits

To the mining or petroleum engineer, the profit of exploitation is defined by the difference between the price received for his product and the pecuniary costs of recovering the natural material and turning it into a salable product. To society, however, the profit from mining (including oil and gas extraction) can be defined either as an energy surplus, as from the exploitation of fossil and nuclear fuel deposits, or as a work saving, as in the lessened expenditure of human energy and time when steel is used in place of wood in tools and structures. In this context, the exploitation of earth resources for display, adornment, or monetary backing is a deficit operation, financed by energy profits from other kinds of mining.

The ultimate limit to exploitation of earth resources then is the limit of net energy profit (or work savings). When it takes more energy to find, recover, process, and transport the fossil fuels than can be gotten from them in useful form, there will be no more oil, gas, or coal resources. When it takes so much energy or work to produce a nonenergy material that one must sacrifice other, more needed, items or services to pay for it, there will be no more resources of that material. Short of this energetic limit, one or both of two other limits may intervene. First is the limit of comparable utility. A resource is a resource only while it can be used to perform a function desired by man better or more cheaply than can another substance. If the energy cost of an earth resource such as crude oil rises to a level at which another substance, such as synthetic crude oil from coal, can be substituted in adequate volume at a lower cost for comparable utility, substitution will take place, with the first resource reverting to a mere geochemical anomaly and the source of the replacing substance becoming a resource.

The limit to a resource also may be determined by the unwillingness of society to pay the cost of its exploitation, even though an energy surplus (or saving) might be obtained thereby. According to Sahlins (*4*) many primitive societies preferred to take their energy surplus in leisure rather than in goods (stored energy or work) and deliberately abstained from exploiting available potential resources that could have increased their surplus. Some primitive agricultural societies still do this. Rappaport (*5*) has described a New Guinean society in which agricultural surplus is taken in leisure when the option of taking it in meat or goods is clearly open. A modern decision to forgo the calculable energy benefits of the breeder-reactor power plant would again invoke this limit of living-level degradation, a limit that comes into play when a society is not willing to pay the total costs of production—because so doing would, it is judged, lower the level of living more than would forgoing use of the resource.

Effects of Technology and Cheap Energy

To some, the history of nonrenewable resource exploitation seems to contradict the idea of an energetic limit short of mining common rock and "burning" seawater (*6*). During the past 150 years large increases in the earth-resource base of industrialized society have been attained. By in-

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creasing the efficiencies of discovery, recovery, processing, and application of such resources, we have been able to find and exploit leaner, deeper, and more remote deposits. By discovering and developing new methods of utilizing previously worthless materials we have created resources where none existed. Important in this rapid technologic advance has been a progressive lowering of the cost of energy per unit of work or useful heat obtained. Cheaper energy, along with technological ingenuity and discovery, has greatly extended the availability of nonenergy resources. In 1900 the lowest grade of copper ore economically minable was about 3 percent, today the economic cutoff has fallen to about 0.35 percent; at that grade each ton of refined copper produced requires the breaking, transport, and milling of almost 300 tons of rock and, in addition, the removal of perhaps an equal amount of waste or barren rock. A great deal of energy—about 26,000 kilowatt-hours (*7*), the equivalent of the energy in about 4 metric tons of Wyoming coal—is required to produce a metric ton of copper today, but the cost of that energy is still low compared to the cost of supporting the equivalent in men and mules.

Many past forecasts of the exhaustion of one or more earth resources have come to appear almost wildly inaccurate in the light of later production. Forty years ago, geologist C. K. Leith, for example, called attention to the coming exhaustion of U.S. mineral resources, claiming (*8*, p. 169) that "despite a magnificent endowment [of metals and fuels], depletion is further advanced than even mining men generally realize." At the time Leith wrote, proved reserves of crude oil, zinc, and lead in the United States were 15 to 20 times larger than annual production rates, the Lake Superior iron ores appeared to have less than 20 years of measured supply remaining, and known copper reserves were about 40 times the 1934 production. Leith went on:

> Further discovery and the use of lower grade resources will extend the life of most of these resources, but the range of possibilities is now pretty well understood, and with maximum allowance for such extension, the figures are sufficiently small, when compared with what we hope will be the life of the nation, as to be matters of public concern. . . . Discovery has not stopped, but the rate has been slowing. . . . Of 33 metal-mining districts that have yielded the greatest wealth to date only 5 have been discovered since 1900 and none at all since 1907. . . . The rate of discovery of oil and gas continues high . . . but the chances of finding another East Texas or Kettleman Hills are not promising.

Well, what happened? Since 1935, the United States has produced more zinc than it did before that year. In 1974 the U.S. mine production of zinc (Table 2) could have been maintained for 61 years on the then-known reserves; the ratio of domestic reserves to primary consumption (defined as domestic demand less the recycled or secondary supply) stood at 24, despite the fact that demand had soared.

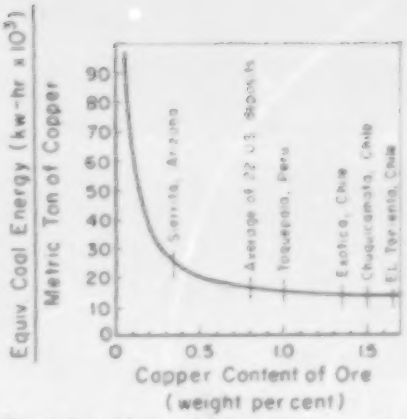

Fig. 1. Equivalent coal energy requirements for different grades of copper sulfide ores. Grades of some copper deposits are shown (*25*, figure 2).

Although U.S. lead production since 1935 does not equal the pre-1936 total, the ratio of measured reserves to primary consumption in 1974 was 67, and the 1974 mine production could have continued for 87 years without further discovery.

The Lake Superior iron ore of Leith's day has been virtually exhausted, but it has been largely replaced by taconite, a low-grade iron-bearing rock not considered to be ore in 1935. The 1974 ratio of measured reserves to U.S. iron-ore consumption was 14, and at the 1974 rate of U.S. mine production, the reserves would last about 24 years.

Table 1. Ratio of cutoff grade (the lowest concentration economically recoverable in 1975) to crustal abundance for selected elements. Except for carbon, which is from Mason (*27*), crustal abundances are from Lee and Yao (*28*). Values are parts per million (ppm).

Element	Crustal abundance (ppm)	Cutoff grade (ppm)	Ratio
Mercury	0.089	1,000	11,200
Tungsten	1.1	4,500	4,000
Lead	12	40,000	3,300
Chromium	110	230,000	2,100
Tin	1.7	3,500	2,000
Silver	0.075	100	1,330
Gold	0.0035	3.5	1,000
Molybdenum	1.3	1,000	770
Zinc	94	35,000	370
Uranium	1.7	700	350
Carbon	320	100,000	310
Lithium	21	5,000	240
Manganese	1,300	250,000	190
Nickel	89	9,000	100
Cobalt	25	2,000	80
Phosphorus	1,200	88,000	70
Copper	63	3,500	56
Titanium	6,400	100,000	16
Iron	58,000	200,000	3.4
Aluminum	83,000	185,000	2.2

Since 1935, more copper has been mined in the United States than before. Based on 1974 figures, the ratio of reserves to primary consumption was 50, and U.S. mine production could have continued at the 1974 level for 57 years without new discoveries.

More recoverable crude oil (*37.3* billion barrels) has been discovered since 1935 than was produced from 1857 through 1934 (62.0 billion barrels). At the end of 1974, however, the ratio of proved reserves to 1974 production was only about 11. Perhaps more significantly, the ratio of proved domestic reserves to 1974 consumption (of both domestic and foreign petroleum) was only 7.7.

In regard to these major earth resources, the United States in 1975 was substantially worse off than it was in 1935 only in crude oil. Despite large increases in consumption rates over the past 40 years, we now have many more "years" of lead reserves than we did 40 years ago, as well as about 25 percent more years of copper and zinc reserves—even if we were abruptly deprived of all imports of these metals. With continued imports, our iron-ore reserve position is much better than it was 40 years ago; without imports, we have lost only 4 years of reserves in 40 years.

In the short term, and except for oil, Leith appears to have been wrong. The continuous-creation school of resource analysts would classify him as a doomsayer of the past whose forecasts went awry for the same reason that those of the present-day Cassandras will miss the mark, a lack of understanding of the impact on reserves of continuously improving technology, which geologist Nolan (*10*) once called "the inexhaustible resource."

The view that advances in technology, stimulated by the market economy, will prolong the availability of a mineral commodity almost indefinitely or will provide adequate substitutes when rising cost begins to slow demand, has much evidence in its favor and many strong adherents (*11*). There is currently an oversupply of both copper and crude oil in the world, and the supply of ores of iron and aluminum, despite enormous increases in the production and consumption of both during the past 50 years, seems almost boundless.

Why, then, do some (*12*) persist in the opposite view, that physical limits will slow or halt the development and utilization of most earth resources long before crustal concentrations can be regarded as reserves? Perhaps it is because they are impressed by the steepness of the geochemical gradients at the margins of most ore

Table 2. Comparison of the ratio of reserves to production (R/P) in 1934 with the same ratio and the ratio of reserves to primary consumption (R/Cp) in 1974 for five major earth resources. Figures are for the United States. Figures for copper, iron ore, lead, and zinc are in thousands of metric tons; for crude oil, in millions of barrels. The 1974 statistics, except for crude oil, are from the Bureau of Mines (*29*); values have been converted to metric tons. Crude oil production and reserve figures are from (*9*), net imports and primary consumption from (*30*). The 1934 approximate R/P figures are from Leith (*8*).

Resource	1934 R/P approximate	1974 Domestic mine (well) production	1974 Net imports (primary and secondary)	1974 Domestic secondary supply	1974 Domestic reserves (R)	1974 R/P	1974 Domestic primary consumption (Cp)	1974 R/Cp
Copper	40	1,441	391	455	81,800	57	1,640	50
Iron ore	18	83,000	46,000	NA*	2,000,000	24	140,500	14
Lead	15–20	615	82	564	53,600	87	800	67
Zinc	15–20	447	655	77	27,300	61	1,150	24
Crude oil	15–20	3,043	1,268	NA*	34,250	11.2	4,447	7.7

*NA, not applicable

and fossil-fuel deposits, by the fact that such deposits do not show a compensating increase in tonnage of reserves (calculated as recoverable metal or fuel) as grade decreases, by the environmental limitations on their origin, and by the fact that the energy or work cost of recovery increases exponentially with decreasing grade of the ore or with increasing cumulative recovery in the case of crude oil.

Examples of Exploitation Limits

The so-called porphyry copper mines, which now produce more than half the world's copper, are worth looking at in the context of exploitation limits. Although differing considerably in detail, they have certain features in common (*13, 14*). They are sharply restricted in age of formation to three periods, or pulses, within the range of 30 million to 200 million years ago. They are associated with small intrusive bodies of stocklike form, averaging 1200 by 2000 meters in outcrop. The ore bodies tend to be pipelike and oval in plan, with dimensions of approximately 1000 by 2000 meters. Mineralization is in concentric zones (*15*), with the copper content in the center of the body reaching ten times that at the outer edge of metallization (*16*). Vertical dimensions can reach 3000 meters, but the pipe narrows downward. If, as Sillitoe (*17*) believes, the porphyry copper deposit spans the boundary between the plutonic and volcanic environments, it occupies a very special geologic position indeed, sharply limited in both time and space.

The Toquepala and Cuajone mines in Peru are typical of the porphyry coppers (*18, 19*). The mass of mineralized rock in these deposits has the shape of an inverted and truncated cone, within which the copper content ranges from 1.32 percent to less than 0.45 percent, the present cutoff grade, below which mining and processing would be unprofitable. Rock containing between 0.20 and 0.45 percent copper is, however, being mined and stockpiled for later leaching by sulfuric acid. Below an average of about 1 percent copper, the copper content of the ore (Table 3) decreases sharply as the grade drops. The deposits, although the ore minerals are irregularly disseminated through them, have rather sharp geochemical boundaries, and the diameter of the mineralized cone decreases downward. The energy cost, per kilogram or ton of refined copper, of mining and milling the ore increases inversely with grade and directly with depth.

At Cuajone, if the ore cutoff grade were to fall from the present 0.45 percent to 0.20 percent (the upper and lower boundaries of the 102 million tons that average 0.32 percent), the total copper recovery would be increased by only 7 percent. At Toquepala, a similar lowering of the cutoff grade would increase recoverable copper by less than 4 percent. Because economies of scale appear to have been exploited fully, and because energy costs are rising, it does not appear likely that the ore reserves in these mines will be extended much either by technological advances or rises in the price of copper.

A tonnage-grade analysis of known North American porphyry copper deposits (*20*) indicates that 70 percent of the copper metal is in deposits above 0.7 percent copper; lower-grade deposits do not represent increasingly larger amounts of copper, but the reverse. Analyses of the known deposits of the two other principal types of copper deposits, strata-bound and massive sulfide, suggest similar tonnage-grade relations (*21, 22*, p. 167). Significant, too, is the fact that the rate of additions to reserves of copper metal appears to have been falling off since 1960, during a period when the price of copper has risen strongly; here it is important to distinguish between tonnage of ore and tonnage of contained metal. Many more deposits will need to be found, at a faster pace than recently, if copper production is to continue at high levels into the coming century. Furthermore, there appears to be a geochemical barrier to copper recovery at about 0.1 percent copper (16 times the geochemical background),

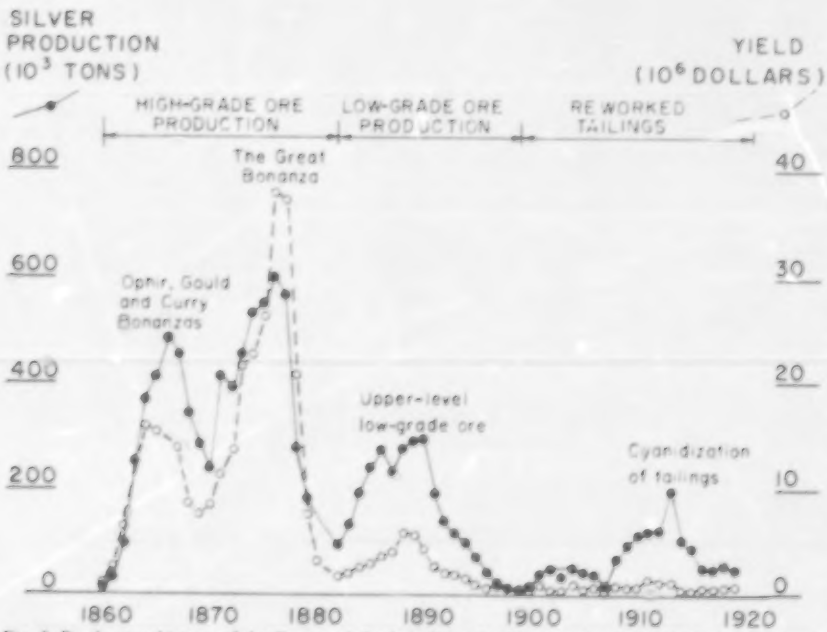

Fig. 2. Production history of the Comstock Lode in Nevada. The data for 1860–1881 are from Lord (*31*); the data for 1882–1920 are from Smith (*32*).

below which most copper is in solid solution in common silicate minerals and is not amenable to selective physical or chemical extraction (*22*, p. 129).

The basic question in forecasting earth-resource exhaustion is whether or not the energy-profit limit will be reached, or demand will cease, short of attempts to extract the desired resource from ordinary rock and seawater. For some resources, we can say with assurance that the energy-profit limit will be reached long before ordinary rock can be mined profitably. The fossil fuels are the best and most important examples. The energy potential represented by the average concentration of carbon in the earth's crust is 2.9 kilowatt-hours per metric ton, not nearly enough to crush and grind it to liberate the carbon for use. In large modern copper-ore mills, grinding and classification (separation) alone require about 26 kilowatt-hours (coal equivalent) per metric ton of ore milled. We can thus be sure that the sharp physical boundaries that characterize coal and petroleum deposits are also economic boundaries. In fact, for most petroleum deposits the economic limit of exploitation lies within the deposit rather than at its margins: oil clings so tenaciously to the pore walls of reservoir rocks that to flush it all out would require more energy than can be gotten from it. The curve of incremental recovery against energy cost is steeply exponential for so-called tertiary recovery techniques, and to achieve an average cumulative recovery ratio of even 40 percent from American reservoirs will require much higher prices for oil than can now be foreseen (*23*).

Table 3. Relations of ore grade, copper content, and mining and milling energy at Cuajone mine, Peru. Values in the last column are Δ per short ton of copper, where Δ is the energy required to mine and mill a short ton of 1.00 percent copper ore. To convert short tons to metric tons, divide by 1.1023.

Average grade (%)	Tonnage (short tons) ($\times 10^6$)	Copper content (short tons) ($\times 10^3$)	Energy needed to mine and mill (Δ/ton)
1.32	20,000	264	0.76
0.99	430,000	4,257	1.01
0.32	102,000	326.4	3.13
< 0.20*	1,057,000	66.6*	> 16,000

*Mostly barren overburden of post-ore volcanic rocks, calculated at crustal abundance for copper content and energy needed.

On the other hand, there are very large low-grade deposits of uranium in which the potential energy is more than sufficient to break, transport, and pulverize the rock, and then to recover the uranium. Breeder reactors converting 60 percent of the potential energy of uranium to thermal energy and 40 percent of that to electricity could produce more than 5500 kilowatt-hours per metric ton of average crustal rock, which might allow an energy profit to be returned. The question here is the amount of energy required for mining and milling very low grade ore. Not only does the tonnage of ore necessary to produce 1 ton of metal increase hyperbolically as the grade decreases (*24*, *25*, p. 10) (Fig. 1), but the energy input per ton of ore ground increases as the size required to liberate small particles of ore decreases (*26*). As ore grade decreases, the percentage of the valuable metal recovered in milling decreases; this falling off in recovery efficiency has the effect of increasing the energy cost per unit of refined metal. Finally, the ore generally gets harder to break and more expensive to lift as mining goes deeper; therefore, the energy costs of mining (per ton of recovered metal) tend to increase as exploitation continues.

The energy required to produce refined metal from low-grade ores becomes extremely high at grades that, except for iron and aluminum, are well above the corresponding crustal abundances.

Except in the cases of strip-mined coal and Persian Gulf oil, the energy costs of obtaining useful energy are rising as fund sources grow deeper, leaner, and more recalcitrant or refractory and as income

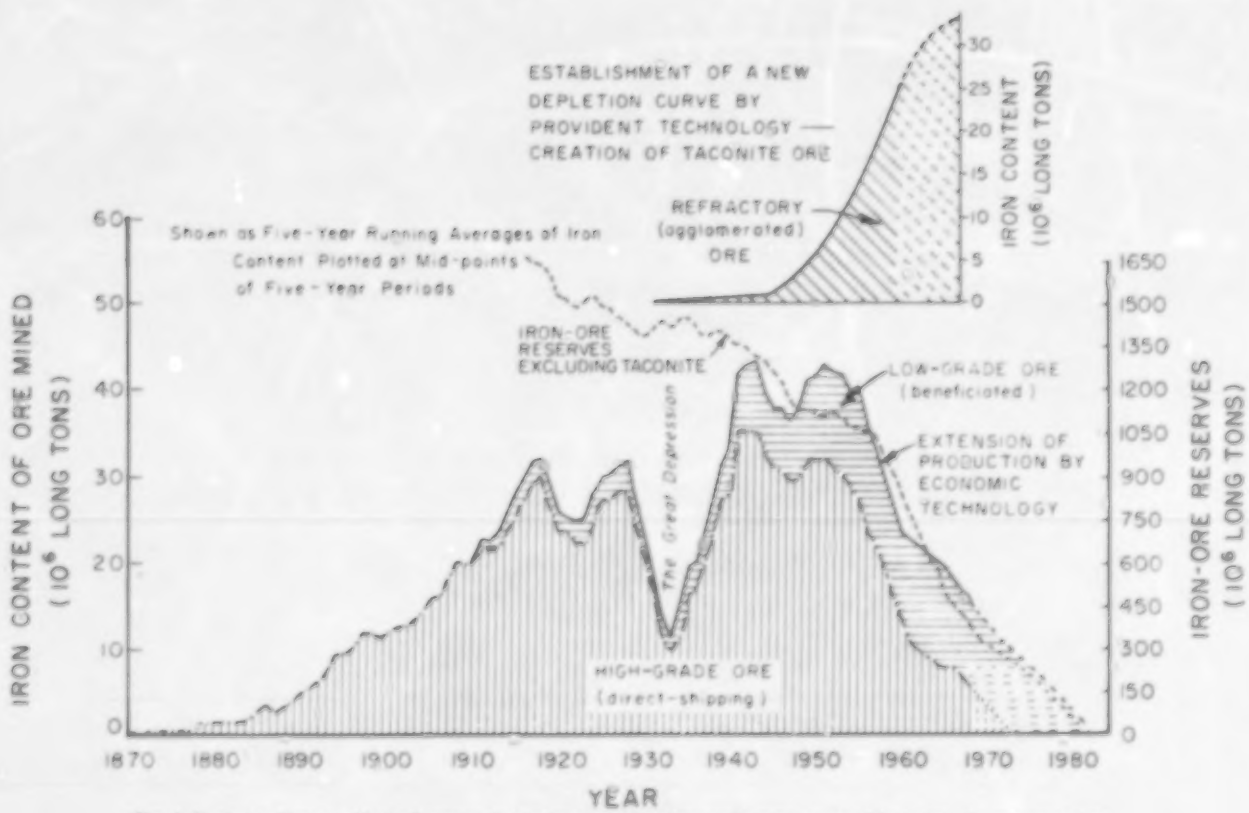

Fig. 3. Depletion history of Lake Superior district iron ore, showing overlapping stages of depletion of a mining region.

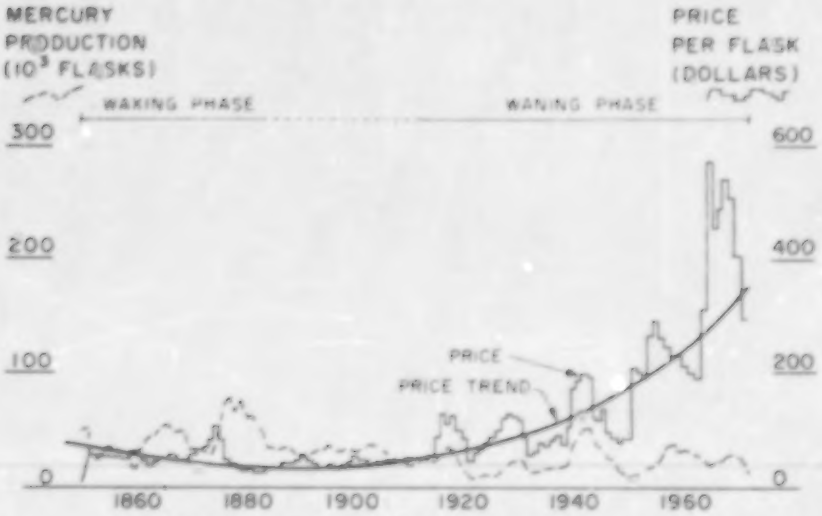

Fig. 4. Production and price history of mercury in the United States (*35*).

sources become limited. Coal exploitable by stripping and Persian Gulf oil are clearly finite, and production of both is likely to wane within 25 to 50 years. Increased costs of obtaining useful energy and higher work costs of exploiting leaner or more refractory materials will tend to raise present ore cutoff limits and thereby to reduce reserves, while technologists continue the struggle to lower cutoff grades and augment reserves. Only a breakthrough of provident technology that results in a substantial lowering of energy costs would reverse what appears to be a tightening of the drawstring on nature's bag of nonenergy resources. The breeder reactor may represent such a breakthrough.

Depletion Histories

The history of a mining district or of an oil field has a beginning and an end, separated by a productive period. Some histories end abruptly, others are drawn out. Resurrection is rare. The history of the Comstock silver lode (Fig. 2) illustrates a simple depletion pattern characteristic of high-grade, sharply bounded, vertically limited mineral deposits. The Comstock vein system, a candelabrum with tabular branches, is typical of fractures that fill with ore minerals at shallow depths; the system is rich and intricate near the surface, barren and simple a few thousand feet below. Its production history shows three distinct stages. In the first stage, during which the greatest part of the lode's total value was extracted, high-grade ore was mined at a fast rate. In the second stage, it became possible because of technological improvements to mine lower-grade material bypassed in the first stage. In the final stage, waste material and some very low grade ore were processed by a new technology, but little was added to the value already produced.

Somewhat different from the history of the Comstock is that of the Lake Superior iron district. Depletion of the rich "direct shipping" ores of that district is almost complete (Fig. 3). These ores, created by a geologic process related to groundwater levels and to the particular geologic configurations of the district, had sharp physical boundaries that coincided with economic limits. In the waning stage of production, upgrading of low-grade material into shippable concentrates added substantially to total production, but delayed exhaustion by only a few years. However, the Lake Superior district has been revived through a technological breakthrough that created a very large resource out of a previously worthless iron-bearing rock called taconite. Such provident technology can be effective only where there is a deposit, already concentrated by natural processes, characterized by a refractory host or reservoir rock. Taconite production, now in its youthful stage, will also pass through maturity to exhaustion.

Iron and aluminum are abundant elements in the earth's crust. For each, there are several kinds of geologic concentrations that represent actual or potential resources; consequently, for each we may expect the depletion history to consist of a series of production-history curves, as availability and cost dictate a steplike descent from high-grade hematite to taconite to iron-rich intrusive bodies, and from bauxite to alunite to high-alumina clays.

When we move in scale from an individual mining district to a country, we find fewer examples of complete production cycles. Mercury, however, is an essentially exhausted resource within the United States, and its production history shows some significant relations to price (Fig. 4). Exploitation of mercury went through three phases: a waxing phase, during which increases in production caused the price to fall; a mature phase, during which price and production were more or less in equilibrium; and a waning phase, during which successive surges in price evoked progressively weaker responses in production.

The waxing phase represents a period when real cost falls because of new discoveries, technological improvements, and economies of scale. The falling cost stimulates demand. Increased production hastens the exhaustion of high-grade, low-cost deposits and puts pressure on technology to counter increasingly adverse geologic and geographic conditions. When technology begins to lose the battle, real cost rises and the waning phase is entered. Prices rise with increasing costs of production and demand falls. Sharply rising prices stimulate the search for a substitute, either imports of the same substance or domestic production of a replacement material; if a substitute is found, domestic production of the resource ceases; if not, it is stretched out, diminishing slowly as demand wanes.

The relation of production and price curves for U.S. silver is similar to that for mercury (*19*, p. 21) and the curves for crude oil are developing in like fashion. During the waxing phase of U.S. oil production, gluts of oil drove the price down to or below the actual cost of production. Proliferation of automobiles and trucks was stimulated by cheap fuel, and demand grew. The passage to the waning phase, about 1971, was abrupt because of the large cost differential between domestic and foreign crude oil at a time of strongly rising demand, a differential that forced a rapid shift from domestic production to imports. Current, artificially high, world crude-oil prices have encouraged exploration for new domestic reserves and have stimulated new efforts to recover more oil from existing wells. It is almost certain, however, that we shall not see a production response equivalent to the price rise because the costs of finding and recovering crude oil (and natural gas) increase exponentially with depletion. If the present cartel of oil exporting countries collapses and world oil prices fall sharply, the end of the U.S. production curve will be abrupt. If the cartel does not collapse, but an adequate supply of substitute energy, say from coal or oil shale, is developed at or near the present price of crude oil, the end of U.S. crude production will be slower but similarly assured.

Conclusion

In view of the geologic and geochemical constraints on the occurrence of economic deposits of minerals and energy resources, and the advanced nature of present exploitation techniques, we must conclude that such resources are finite. The "endlessly retreating" interface between ore and almost-ore that some optimists have described could be validated only if the cost of useful energy would endlessly and acceleratingly decrease. On the other hand, the question "When will we run out?" bespeaks a misunderstanding of geologic resource limits. The world will not run out of geologic resources. They will merely become more expensive. As they become more expensive their utility will diminish, either by human decision or by failure to achieve an energetic profit. How expensive a geologic resource becomes, and how fast its real cost rises, will depend on a combination of geologic and technological factors. Depletion (rise in cost) is swift for those materials found mainly in sharply bounded, highly concentrated deposits—especially swift if they cannot be recycled after use. Depletion is slow for abundant materials found mainly in deposits of relatively low geochemical concentration with gradational boundaries—especially slow if they can be recycled after use.

Summary

Despite the fact that strongly positive geochemical anomalies are relatively small and rare and appear to be restricted to the outermost part of continental crusts, the history of economic exploitation of nonrenewable resources over the past 200 years is, in general, one of decreasing costs and increasing reserves. However, the direct energy or work costs of recovery have been rising, slowly for a long while, then more rapidly as the number of tons of ore required to produce a ton of refined metal has started to rise more steeply with decreasing ore grade. The seeming paradox of decreasing total costs and increasing work costs is explained by a long record of decreasing real costs of the energy used to extract and process nonrenewable resources. Now that energy resources themselves are beginning to cost more in work, now that the efficiencies of energy conversion appear to be nearing limits dictated by the strength of materials and the laws of thermodynamics, and now that the work costs of recovery, at least for some resources, are moving up the steeper parts of exponential curves, the nature of the limits to exploitation of nonrenewable resources is beginning to be recognized.

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The Age of Substitutability

What do we do when the mercury runs out?

H. E. Goeller and Alvin M. Weinberg

Two conflicting views dominate our perception of man's long-term future. The "catastrophists" believe that the earth's resources will soon be exhausted and that this will lead to the collapse of society. The "cornucopians" argue that most of the essential raw materials are in infinite supply: that as society exhausts one raw material, it will turn to lower-grade, inexhaustible substitutes. Eventually, society will subsist on renewable resources and on elements, such as iron and aluminum, that are practically inexhaustible. According to this view, society will settle into a steady state of substitution and recycling. This asymptotic society we call the Age of Substitutability. In this article we examine these questions; although much of what we say must be regarded as tentative and speculative, we expound these views in the hope that they will stimulate further study.

We are cornucopian, even in this era of dwindling resources and in spite of dire predictions (*1*, *2*). We came to this position some 25 years ago, after reading Darwin's *The Next Million Years* (*3*). Darwin insisted, as do some present-day forecasters and systems modelers, that short-term forecasting was impossible [as well as disconcerting for the forecaster, who presumably would live to see his forecasts tested against fact]. But very long range forecasting, in which fluctuations in human experience are blips on an underlying statistical state, could be done in the same sense that statistical mechanics predicts the future of a big ensemble. Darwin asserted that over the very long term, man's fate, on the average, was predestined by the Malthusian disequilibrium: man procreates in a finite world. Man's continual scramble for finite resources condemns him to eternal social instability, violence, and brutishness.

Darwin realized, as do all neo-Malthusians, that there was no panacea; no solution could work unless population leveled off. But even this was not enough: as resources dwindled, the pressures on what remained would grow. Darwin also recognized, as did H. G. Wells some 40 years earlier (*4*), that an inexhaustible source of energy would be necessary—perhaps even sufficient—to rescue man from the resource catastrophe. Most of the materials that man uses, such as iron and aluminum, are found in nature in an oxidized state. To reduce these oxides, to extract iron or change alumina to aluminum, requires energy (more accurately, free energy). Thus, man's economic transaction with nature involves expenditure of free energy, and as his high-grade resources dwindle, he expends more energy. Darwin saw only one possible inexhaustible source of energy: nuclear fusion. Here we disagree: there are other inexhaustible sources of energy (notably the breeder reactor, and possibly solar energy) that, if developed, would allow man to avoid the hopeless future Darwin predicted.

The Principle of Infinite Substitutability

The catastrophists, when discussing a particular resource such as aluminum, usually say that when all our bauxite has been used, we shall have to live without aluminum. Thus, according to Meadows *et al.* (*1*, p. 71), "The effect of exponential growth is to reduce the probable period of availability of aluminum, for example, from 100 years to 31 years." This cannot be correct. As geologist Frasché said in 1962 (*5*), "Total exhaustion of any mineral resource will never occur. Minerals and rocks that are unexploited will always remain in the earth's crust. The basic problem is how to avoid reaching a point where the cost of exploiting those mineral deposits which remain will be so costly, because of depth, size, or grade, that we cannot produce what we need without completely disrupting our social and economic structures."

We can conceive of depletion of resources and substitution in three stages. Stage 1, which almost surely will persist for the next 30 to 50 years, is a continuation of present patterns of use of the nonrenewable resources. During stage 2, when society still would depend on reduced carbon and hydrogen found in nature—that is, coal—there would be little oil and gas, and people would begin to turn away from widespread use of a few of the nonferrous metals and toward much greater use of alloy steels, aluminum, magnesium, and titanium. Stage 2 might last several hundred years. Finally in stage 3, the Age of Substitutability, all the fossil fuel would be exhausted, society would be based almost exclusively on materials that are virtually unlimited. It is our basic contention that, insofar as limits to mineral resources can be discerned, the condition of life in stage 3 would not be drastically different from our present condition: we have the physical possibility of living in the Age of Substitutability and not "completely disrupting our social and economic structures." To reach this state without immense social disruption will, however, require unprecedented foresight and planning.

A convenient way to place the matter in perspective is to examine the "chemical" composition of one molecule of "demandite," the average nonrenewable resource humans use. We take the total number of moles of each element that is extracted from the earth, the sea, and the air, and from this compute the average mole fractional composition of the average nonrenewable resource. Similarly, we can define the average metal, "avalloy." We exclude renewable resources: agricultural products, wood, and water. In Tables 1 and 2, we give the chemical formulas and other properties of demandite and avalloy for 1968 (*6*).

Now let us compare the composition of these average materials with the average composition of the earth's crust, the sea, and the air (Table 3). Actually, the resource situation is even better than this comparison implies because many elements, including the majority of those most used in demandite, may be obtained in much higher concentration in sources other than average rocks; these are summarized in Table 4.

The data in Tables 3 and 4 show that of the 13 most widely used elements, only extractable CH_x and phosphorus are not essentially inexhaustible; whereas oxidized carbon and hydrogen are very common, extractable CH_x is rare—only 25 to 30 parts per million (ppm) in the first kilom-

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ater of the earth's crust. Yet extractable CH_x dominates demandite: 80 percent of U.S. demandite and 67 percent of world demandite is CH_x. Thus, when we speak of exhausting our resources, by far the most important scarce resource is extractable CH_x. Since energy can reduce CO_2 and H_2O to CH_2, we can paraphrase the basic point in both Wells's and Darwin's Malthusianism: the primary resource shortage is one of reduced CH_x or its equivalent, energy. Shortages of almost all other minerals are of second order compared to shortages of CH_x.

The central position of reduced carbon, or of reducing agents, is seen also when we examine the chemical composition of avalloy. Iron atoms constitute about 66 percent of U.S. avalloy, aluminum atoms 8 percent: these two inexhaustible metals constitute 94 percent of the total. Extracting iron from its oxides by presently used processes requires reduced carbon, and this accounts for about 12 percent of all coal used in the United States. Although avalloy itself is made largely from iron and aluminum, producing it requires reduced carbon, which is a rare material, or some other source of energy.

We now state the principle of "infinite" substitutability. With three notable exceptions—phosphorus, a few trace elements for agriculture, and energy-producing fossil fuels (CH_x)—society can subsist on inexhaustible or near-inexhaustible minerals with relatively little loss of living standard. Society would then be based largely on glass, plastic, wood, cement, iron, aluminum, and magnesium; whether it would be anything like our present society depends on how much of the ultimate raw material—energy—we can produce and how much energy will cost, both economically and environmentally.

To give substance to so broad a claim it is necessary to examine in detail, not simply in principle, exactly how people could live without a particular finite resource. We do not do this here; instead, we quote from previous work on the subject by Goeller (*7*).

Certainly there are no substitutes for the elements required to sustain life. The most important of these are H, O, C, and N; next come Ca, P, Cl, K, S, Na, and Mg, which constitute less than 1 percent of the total in living things. Besides these there are at least 13 required trace elements: F, Si, V, Cr, Mn, Fe, Co, Cu, Zn, Se, Mo, Sn, and I. Modern agriculture requires large amounts of Ca, N, K, and P, plus relatively small quantities of some of the trace elements. Of the major life-sustaining elements, only phosphorus is not on our list of inexhaustible elements. The average natural abundance of phosphorus in rocks is about 1000 ppm; if society eventually had to depend on average phosphorus, the costs of agriculture might become intolerably high. However, high-grade resources of phosphorus are very large: the present resource-to-demand ratio is 500 years for world reserves and an additional 800 years for potential resources. In addition, even though speculative resources are poorly known, they are regarded as very large (but considerably smaller than fixed nitrogen from air or potash from seawater). Nevertheless, phosphorus can hardly be regarded as inexhaustible. This led Wells *et al.* (*8*) many years ago to imply that ultimately we shall have to recycle bones as fertilizer, and we are in no position to refute this view.

With regard to the trace elements that are present in soil and are needed only at low concentrations, modern agriculture slowly depletes these elements. In the near term, shortages can undoubtedly be supplied from inorganic sources; in the long run, we shall undoubtedly be forced to return agricultural and animal wastes to the soil, particularly for the trace elements with limited resources, such as copper, zinc, and cobalt.

Beyond these nonsubstitutable elements, we use many rather scarce metals because of their special properties: copper because it is a good electrical conductor; nickel, chromium, and niobium because they con-

Table 1. Properties of demandite, the average nonrenewable resource used in 1968. Values apply only to new metal from ore. Data are derived, with some modifications, from (*6*). The composition of demandite, in mole fractions, is for the United States

$(CH_{1.\ldots})_{\ldots}$ $(SiO_2)_{\ldots}$ $(CaCO_3)_{\ldots}$ $Fe_{\ldots}$
$Al_{\ldots}$ $(Cu, Zn, Pb)_{\ldots}$ $Mg_{\ldots}$
$N_{\ldots}$ $O_{\ldots}$ $Na_{\ldots}$ $Cl_{\ldots}$
$S_{\ldots}$ $P_{\ldots}$ $K_{\ldots}$ $X_{\ldots}$

and for the world

$(CH_{1.\ldots})_{\ldots}$ $(SiO_2)_{\ldots}$ $(CaCO_3)_{\ldots}$ $Fe_{\ldots}$
$Al_{\ldots}$ $(Cu, Zn, Pb)_{\ldots}$ $Mg_{\ldots}$
$N_{\ldots}$ $O_{\ldots}$ $Na_{\ldots}$ $Cl_{\ldots}$
$S_{\ldots}$ $P_{\ldots}$ $K_{\ldots}$ $X_{\ldots}$

where X represents all other chemical elements, highest in order of demand are Mn, Ba, Cr, F, Ti, Ni, Ar, Sn, B, Br, and Zr; for all others the demand is < 100,000 tons a year (world) or 30,000 tons a year (United States).

Property	United States	World
Total quantity (× 10^9 tons)	3,360	17,300
Total value ($ million)	42,200	158,500
Average unit value ($/ton)	12.55	9.16
Average energy used for recovery (kwh/ton)	1,140	800
Total quantity (× 10^9 ton moles)	140.4	551.3
Average molecular weight	23.9	31.4
Per capita consumption (tons)	17	5
Per capita energy and energy rate		
(kwh)	18,800	3,800
(kw)	2.14	0.43

Table 2. Properties of avalloy, the average virgin metal used in 1968. Values apply only to new metal from ore. Data are derived from (*6*). The composition of avalloy, in mole fractions, is for the United States

$Fe_{\ldots}$ $Mn_{\ldots}$ $Si_{\ldots}$ $Cr_{\ldots}$ $Ni_{\ldots}$ $X_{\ldots}$ $Al_{\ldots}$
$Cu_{\ldots}$ $Zn_{\ldots}$ $Pb_{\ldots}$ $Sn_{\ldots}$ $Mg_{\ldots}$ $Ti_{\ldots}$ $Y_{\ldots}$

and for the world

$Fe_{\ldots}$ $Mn_{\ldots}$ $Si_{\ldots}$ $Cr_{\ldots}$ $Ni_{\ldots}$ $X_{\ldots}$ $Al_{\ldots}$
$Cu_{\ldots}$ $Zn_{\ldots}$ $Pb_{\ldots}$ $Sn_{\ldots}$ $Mg_{\ldots}$ $Ti_{\ldots}$ $Y_{\ldots}$

where X includes all other ferrous metals, and Y all other nonferrous metals.

Property	United States	World
Total quantity (× 10^9 tons)	85.6	424.3
Total value ($ million)	16,050	75,775
Average unit value ($/ton)	187.50	178.60
Average value ($/ton of Fe, Si, Al, Ti, and Mg in avalloy	154.95	145.40
Average energy used for recovery (kwh/ton)	12,300	11,100
Average molecular weight	53.7	54.8
Per capita consumption (tons)	0.43	0.12
Per capita energy and energy rate		
(kwh)	5,290	1,340
(kw)	0.60	0.15

60

fer corrosion resistance and high-temperature strength onto iron, and mercury because it is a metallic liquid at room temperature. Goeller has studied in some detail the extent to which one might substitute for cadmium (*9*), zinc, lead, copper, tin, and mercury (*10*), the main conclusion being that for most of their uses, substitutes derived from inexhaustible or nearly inexhaustible materials are available. To illustrate, we summarize some of the results for mercury.

The Case of Mercury

The average annual consumption of mercury by use and form in the United States, 1964–1973, is given in Table 5. About 2250 tons of mercury were used each year during this period. Suppose we had no mercury—could we survive? Obviously, yes. To persuade ourselves of this we need only demonstrate, for each present use of mercury, a plausible alternative that does not require mercury. These alternatives are listed in Table 5. For example, the largest use of mercury (34 percent or 769 tons per year) is for caustic chlorine production. The diaphragm cell is an alternative that was in wide use before the mercury cell was introduced, and still accounts for 70 percent of the U.S. production of caustic. Diaphragm cells require relatively common materials such as concrete for the cell body, asbestos (which itself is made of calcium and magnesium silicates) for diaphragms, and copper and graphite for electrodes.

Acceptable alternatives are now known for all the major uses of mercury, except possibly for high-performance electric batteries (which would require other scarce materials such as cadmium and silver) or electric switches (*11*). For minor uses, such as in pharmaceuticals, or odd laboratory uses, which amount to <1 to 5 percent each of the total, alternatives have not been sought very seriously because the amount of mercury required is small. We can hardly imagine society collapsing, or even being seriously impeded in the long run, if we have to do without mercurial pharmaceuticals or mercury batteries.

Other Metals

Suppose we played the same game of what-do-we-do-when-the-high-grade-ores-run-out for copper, silver, zinc, tin, and other minor metals. Would the aggregate additional cost—in both energy and dollars—of the substitutes or of the materials themselves be intolerable? To be more specific, let us estimate how much the aggregate unit cost of these metals could rise without causing the cost of avalloy to rise more than twofold.

We can look at the matter by again examining the chemical composition of avalloy. Ninety-five percent of avalloy consists of iron, aluminum, silicon, magnesium, and titanium. These account for 95 percent of the energy per ton of avalloy and 80 percent of the cost per ton. All these materials are in infinite supply, and their ultimate unit cost, in either energy or dollars, can hardly exceed today's unit cost by more than a factor of 2, as shown in Table 6. The remaining 5 percent of avalloy consists mainly of Cu, Zn, Mn, Cr, Pb, Ni, and Sn; these represent about 20 percent of the total value of avalloy (Table 2). At present, extraction from ore represents only about one-half the total cost of the latter metals. The aggregate cost of this group of metals that is sensitive to the grade of ore therefore is not more than 10 percent of the total unit price of avalloy. Thus, even if the price of these materials increased five- to tenfold, the unit price of avalloy would only double.

This is almost surely an overestimate, since we have not allowed for substitution. For example, in 1968 copper accounted for 12 percent of the total cost of avalloy in the United States. But electrical copper is, in the long run, almost entirely replaceable by aluminum, and structural copper and brass are largely replaceable by steel, aluminum, titanium, and plastic. Moreover, manganese (in sea floor manganese nodules) and nickel (in the peridotites) are in nearly infinite supply: it is hard to see how the latter two metals can ever cost more than ten times their present price.

Some substitutes can be identified for the remaining elements—Zn, Cr, Pb, and Sn. Galvanized iron (which uses zinc) can, in good measure, be replaced by plastic-bonded steel; tin plate in cans can be largely replaced by plastic or glass. However, no very good substitute for Cr in stainless steel is presently known. Ultimately, this may force society to substitute titanium (which is in nearly infinite supply) for most uses that are now served by stainless steel. Nevertheless, the remaining elements—Zn, Cr, Pb, and Sn—could increase in cost by a very large factor, and the price of avalloy would still remain within a factor of 2 of its present real cost. This is true also of the remaining nonmetals, the metal oxides, the refractory metals, and the nonferrous by-product metals. Thus we arrive at our basic observation: avalloy and demandite (with the extremely important exception of CH_4) are so heavily dominated by elements derived from infinite sources or elements for which substitutes are available that their unit price is relatively insensitive to depletion of mineral resources. The tentative conclusion to be drawn is that, in principle, our social and economic structures are unlikely, in the long run, to be disrupted because we shall have to exploit lower-grade mineral resources—provided always that we find an adequate inexhaustible source of relatively cheap energy to substitute for CH_4. We put this hypothesis forward, realizing that it is in sharp opposition to the currently fashionable neo-Malthusianism, but we believe the neo-Malthusians have been misled by their habit of lumping all resources together without regard to their importance, ultimate abundance, or substitutability.

Although we can conclude from a global viewpoint that the cost of avalloy in the Age of Substitutability will not be more than two to three times its present price, there will be specific sectors of the economy that are likely to be hit severely. A point requiring additional study is the possibility that some material used in rather small quantity has extremely high leverage on a strategic industry, and that collapse of that industry, or even a drastic increase in the cost of the material, would rock the entire economy. An example might be helium, if we are forced to obtain it from air. If superconducting magnets forever required liquid helium, and if fusion absolutely required superconducting magnets, then a drastic rise in the price of helium might cause a corresponding rise in the cost of energy. However, if the cost of fusion energy exceeds that of solar energy or energy from breeders, then society will choose solar plants or breeders, not fusion, for its primary inexhaustible source of energy. Thus, we cannot accept the view that helium is absolutely essential for the long-term future of our industrial society (*12*).

Recycling

As prices for materials increase, there will be stronger incentives to recycle, to bring the empty bottles back. The remelt energy required to put scrap metal back into productive use is very much less than the energy needed to reduce and refine ores. For magnesium the remelt energy is 1.5 percent of the energy required to win the metal from ore; for aluminum it is 3 to 4 percent; and for titanium it is 30 percent. One must recognize that recycling cannot provide the total answer, since the recovery in each recycle is never 100 percent; in fact, unless recycling is very efficient, it will not make very much difference. If the recovery of copper, say, is 90 percent per cycle, then recycling reduces the required amount of virgin copper to be added to the system

each year by a factor of $(1 - 0.9)^{-1} = 10$. But if recovery is only 40 percent per cycle, this factor is reduced to only 1.7.

Recycling is simplified by human intervention. If materials are not recycled, they become diluted and dissipated in the environment, their entropy increases. Thus, when an intelligent being sorts used material into separate bins, he diminishes the entropy of the original waste material. However, such a macroscopic Maxwell's demon does not change the entropy of mixing appreciably unless he prevents useful materials from becoming dissolved as individual molecules, which then can be widely dispersed in soils or in the oceans.

The Energy Budget

As we exhaust the high-grade materials and have to use lower-grade ones, the energy required to recover our needed materials will grow. Yet, because the composition of avalloy is so dominated by essentially inexhaustible iron and aluminum, the energy required to extract a ton of metal will not grow nearly as much as one might think. Although Frasché was correct that "The extraction of mineral raw materials from low-grade rock is a problem in the application of energy—at a price" (*5*, p. 18), he should have added that the total mass of useful minerals that have a finite resource base is small. Therefore, the effect of their depletion on the entire energy system is less than Frasché's statement might imply.

Of course, even the elements in nearly infinite supply will take more energy to extract as we go from ores to more common rocks. The energy requirements for production and recycling of the abundant metals—Mg, Al, Fe, Ti—and Cu were estimated by Bravard *et al.* (*13*) and are summarized in Table 6. In Table 6 we compare E_L, the amount of energy required to extract a ton of metal from low-grade, essentially inexhaustible ores, with E_H, the energy required to extract the metal from high-grade ores.

It is remarkable that the estimated energy required to produce these metals from essentially inexhaustible sources is in every case not more than about 60 percent higher than the energy required to win the metals from high-grade ores. Even when all the reduced carbon is gone, the ratio for iron—by far the most important metal—is $< \sim 2.0$ (*14*).

Extraction of useful metal from ore involves two separate steps: (i) mining and beneficiation of the ore and (ii) reduction and refining of the metal from the beneficiated ore. Generally the second step requires considerably more energy and expense than the first; for example, to mine and beneficiate 1 ton of iron from presently used magnetic taconite ores requires about 5 percent as much energy as is required for the total production of steel from ore. Thus, the overall energy required is not very sensitive to the grade of ore until the ore becomes extremely dilute, and this will never happen for the inexhaustible metals.

In 1968 the metal industry consumed 8.5 percent of the total energy used in the United States; some 90 percent of this was expended in the production of Fe, Al, Mg, Ti, and Cu. The per capita annual energy expenditure for metal production came to about 8000 kilowatt-hours per person or 0.91 kilowatt per person. However, when only new metal from ores is considered, the primary metal industry accounts for 5.7 percent of total U.S. energy consumption; in this case, per capita energy use is reduced to 5300 kwh per person. In the Age of Substitutability (assuming electrolytic hydrogen, rather than carbon, is used), it seems fair to double the energy expended for these metals—to 10,600 kwh or a rate of 1.2 kw per person—assuming that the amount of metal used per capita and the composition of avalloy remain as they now are (*15*). Even in the Age of Substitutability, the amount of energy required per unit of metal to provide avalloy is hardly twice (rather than 10 or 100 times) that used in the present era. This is because the dominant metals—iron, aluminum, and magnesium—can be extracted from essentially inexhaustible resources, which demand relatively small additional

Table 3. Average mole fractional composition of the earth.

Crust (topmost kilometer on continents)

(CH_2) (extractable) $_{.0006}$		(CH_2) (unextractable)* $_{.0001}$		C (oxidized) $_{.0111}$
O $_{.5007}$	Si $_{.2947}$	H (other) $_{.0014}$	Al $_{.0745}$	Ca $_{.0179}$
Na $_{.0182}$	Fe $_{.0132}$	K $_{.0123}$	Mg $_{.0170}$	Ti $_{.0046}$
Cl $_{.0014}$	S $_{.0004}$	F $_{.0007}$	P $_{.0004}$	Mn $_{.0005}$
X $_{.0004}$				

where X is all other elements, and for which X =

Ba $_{.000077}$	Sr $_{.000034}$	V $_{.000030}$	Zr $_{.000070}$	(Cu, Zn, Pb) $_{.000032}$
N $_{.000021}$	Rb $_{.000021}$	Cr $_{.000018}$	Rare earths $_{.000014}$	(Co, Ni) $_{.000023}$
Other $_{.000071}$				

Seawater (except for water)

Cl $_{.019}$	Na $_{.010}$	Mg $_{.0013}$	S $_{.0027}$	Ca $_{.0004}$		K $_{.0004}$
C $_{.0023}$	Br $_{.0007}$	P $_{.000002}$	Si $_{.0001}$	(Fe, Al, Ti) $_{.000001}$		Other $_{.0004}$

Air (excluding variable amounts of CO_2 and H_2O)

N $_{.7809}$	O $_{.2095}$	Ar $_{.0093}$	Ne $_{.0002}$	(He, Kr, Xe) $_{.0001}$

*(CH_2) (unextractable) represents the very large amount of hydrocarbon in the topmost kilometer of shale. Almost all of this is too dilute to extract with a positive energy balance and therefore cannot be used as a source of energy. In principle, it might be used as a source of CH_2 for petrochemicals.

Table 4. Present or future nearly inexhaustible resources for the most extensively used elements. The last column gives R/D, the resource-to-demand ratio in 1968. As demand grows, these values will be reduced; however, we anticipate that population must eventually level off, which will result in an ultimate leveling off of demands for energy and nonrenewable resources.

Element	Resource	Maximum amount in best resource (%)	World resource (tons)	R/D (years)
CH_2 (extractable)	Coal, oil, gas	< 75	1×10^{12}	2,500
C (oxidized)	Limestone	12	2×10^{17}	4×10^{8}
Si	Sand, sandstone	45	1.2×10^{16}	5×10^{8}
Ca	Limestone	40	5×10^{17}	4×10^{8}
H	Water	11	1.7×10^{17}	$\sim 10^{12}$
Fe	Basalt*, laterite	10	1.8×10^{17}	4.5×10^{8}
N	Air	80	4.5×10^{15}	1×10^{8}
Na	Rock salt, seawater	39	1.6×10^{16}	3×10^{8}
O	Air	20	1.1×10^{15}	3.5×10^{7}
S	Gypsum, seawater	23	1.1×10^{15}	3×10^{7}
Cl	Rock salt, seawater	61	2.9×10^{16}	4×10^{8}
P	Phosphate rock	14	1.6×10^{15}	1,300
K	Sylvite, seawater	52	5.7×10^{16}	4×10^{7}
Al	Clay (kaolin)	21	1.7×10^{17}	2×10^{8}
Mg	Seawater	0.012	2×10^{17}	4×10^{8}
Mn	Sea floor nodules	30	1×10^{12}	13,000
Ar	Air	1	5×10^{15}	2×10^{6}
Br	Seawater		1×10^{14}	6×10^{6}
Ni	Peridotite	0.2	6×10^{17}	1.4×10^{8}

*It must be noted that no process now exists for obtaining iron from basalt, or nickel from the ultrabasic rock peridotite; however, given a century for development of such processes, the likelihood for success seems quite high.

amounts of energy for the extraction.

We have tried to estimate how much the per capita energy budget for producing demandite and desalted water for agriculture would increase in stage 3, although we realize that these estimates are speculative and require more study. In Table 7 we summarize these estimates. We also estimate what these values might be in stage 3, if it is assumed that the per capita use of demandite remains constant but that agriculture requires 100 gallons of desalted water per person per day.

The most striking speculation that we make in Table 7 is that the increase in energy required in stage 3 for nonrenewable resources and desalted water is about 2 kw per person. Adding 2 kw for other uses, we arrive at an estimate that the U.S. per capita energy for all uses in stage 3 might increase from its present 11 kw to 15 kw, and the world per capita use from 1.5 to 7.5 kw. If the world's population grows to 10×10^9, and the entire world reaches half the projected U.S. per capita energy expenditure, the world's total production of energy would amount to about 75×10^9 kw. This is 12 times the present worldwide man-made energy, but still represents only 0.1 percent of the solar energy absorbed and reradiated by the earth.

We shall not dwell on the environmental, technical, and institutional implications of so large a production of energy, since these matters have been discussed elsewhere by many authors (*16*). The main conclusions that we can draw are the following.

1) All fossil fuels, at this rate of energy expenditure, would be consumed within 100 years.

2) The fission breeder, fusion (if feasible), or solar energy, in principle, could carry this energy budget essentially forever.

3) The climatic changes caused by so large a release of energy cannot be predicted with our present knowledge of climatology, although the average increase in world temperature, assuming no changes in albedo, would be about 0.1°C. Whether the effect of such energy output on climate will ever be predictable, even in principle, remains moot.

4) It seems likely that if fission breeders are the basis for the stage 3 energy supply, large institutional changes will be called for so that man can live comfortably with fission, on the scale envisioned here. Thus, if the entire 75×10^9 kw were provided by fission breeders, with each reactor operating at 5×10^6 kw (of heat), the world would have to accommodate 15×10^3 reactors. If each reactor lasted 30 years, then 500 reactors would, in the asymptotic state, be retired each year. This amounts to about ten reactors being built each week. Is this credible? Will we have the land, the waste disposal areas, and the capacity to deal with diversion and with transport of radioactivity on such a large scale?

Although technological fixes (*17*) will ease these problems—for example, cluster siting would make diversion more difficult (*18*)—one can see the point of those such as Mesarovic and Pestel (*2*), who argue that a much more appropriate asymptotic per capita energy demand is the value that now characterizes much of Western Europe: about 4 kw per person. However, we estimated (Table 7) that, in stage 3, loss of CH_x would require an additional 2 kw per person for demandite and agriculture. Since transport, space heating, and cooling would also require more energy in stage 3, we estimate that to achieve the Pestel-Mesarovic world might require perhaps 7 to 8 kw per person, and that the problems enumerated above can hardly be avoided.

Table 5. Average annual consumption of mercury in the United States, 1964–1973.

Uses	Substitutes	Metric tons	Percentage of total
Caustic chlorine production			
Inventory for new facilities*	Diaphragm cells	306	13.5
Makeup†		463	20.5
Subtotal		769	34.0
Electrical (mainly batteries)	Zn-MnO_2-graphite dry cell	598	26.5
Industrial and control instruments	‡	252	11.2
Biocidal paints	Plastic paints, copper oxide paint	299	13.2
Dental amalgams	Metal powders, porcelain, plastics	99	4.4
Agriculture§	Organic biocides	88	3.9
Catalysts	Ethylene process for polyvinyl chloride manufacture	54	2.4
Laboratory use	†	57	2.5
Pulp and paper manufacture‖	Organic biocides	17	0.8
Pharmaceuticals	Sulfur drugs, iodine, and others	17	0.8
Amalgamation‖	Gold recovery by cyanide process	6	0.3
Total		2256	100.0

*Includes small quantities for other uses. †Required to replace that lost in process. ‡Substitution may be based on alternative physical properties and may include bimetallic couples, aneroid barometers, and so forth. Liquid gallium and sodium-potassium alloys may be substitutes at room temperature but not at subzero temperature. §Use of methyl mercury on seed grains has been banned by the U.S. Department of Agriculture; banning of other uses may follow. ‖These uses of mercury were discontinued in the United States in 1971. Other significant uses included mercury fulminate detonators and felt manufacture; both were discontinued decades ago.

Table 6. Energy requirements for the production of abundant metals and copper. Gross energy is estimated at 40 percent thermal efficiency for generation of electricity. The last column gives the ratio of the energy required to extract a ton of metal for low-grade compared to high-grade ores.

Metal	Source	Gross energy (kilowatt-hours per ton of metal)	E_L/E_H
Magnesium ingot	Seawater	100,000	1
Aluminum ingot	Bauxite	56,000	1
	Clay	72,600	1.28
Raw steel	Magnetic taconites	10,100	1
	Iron laterites	13,900	1.17 (with carbon) ~2 (with electrolytic hydrogen)
Titanium ingot	Rutile	138,900	1
	Ilmenite	164,700	1.18
	Titanium-rich soils	227,000	1.63
Refined copper	Porphyry ore, 1 percent Cu	14,000	1
	Porphyry ore, 0.3 percent Cu	27,300	1.95

Mine Wastes

The catastrophists often point out that as we exhaust our higher-grade resources and mine lower-grade rock, mine wastes will lead to disaster. But our analysis points to a rather different outcome. Since CH_x is by far the largest component of demandite, most of the waste from mining is associated with extraction of coal—8 tons of spoil per ton of coal mined in the United States. Thus, in stage 3, when we no longer mine coal, the mine spoil per

person associated with other sources of energy (breeders, fusion, and solar) will be much less than the mine spoil now associated with our energy system (*16*).

As for the mine wastes per ton of avalloy, these can never increase much more than threefold because avalloy is dominated by iron, and high-grade taconite iron ore is only three times as rich as inexhaustible laterite ore. Moreover, the total waste from avalloy mining is only 5 percent of that from coal mining; a threefold increase in avalloy mining waste would still be small compared to the waste from coal mining.

Table 8 gives our estimates for mining spoil at present and in the Age of Substitutability, for the United States and the world. At a per capita energy budget of 7.5 kw in stage 3 the yearly mine spoil per person is 2.4 tons compared to the present 7.4 tons. Thus, one can argue that the world population could increase threefold before the mine wastes in stage 3 equal present mine wastes.

We have not attempted to estimate other pollutants in stage 3. However, since the bulk of air pollution (CO_2, CO, SO_2, trace elements, and fly ash) is the result of burning fossil fuel, there should be less air pollution in stage 3 than at present.

Although our estimates are reassuring, on the average, we are reluctant to leave an impression of facile optimism. The environmental impacts in specific places and specific situations might well be more serious than we have implied.

Conclusions

Most of what we contend is speculation. Yet, there is one aspect of the future which seems to be "scenario-proof": contrary to the assertions of the neo-Malthusians, depletion of mineral resources per se need not create catastrophe, provided man finds an inexhaustible, nonpolluting source of energy. The main problem is how to go from our present state, stage 1, where we have ample CH_x and other resource materials, to stage 3, the Age of Substitutability, without incurring drastic social instabilities. Will we have the capacity and foresight to plan and execute the transition without such instabilities?

It is very well to say that, in principle, substitutes can be found, that even without CH_x our per capita energy budget will not be much greater than it is now. But even factors of 2 in energy budget or price, although they seem small in the long run, can over the short term or in local situations cause great social dislocation.

What is at issue is the effectiveness of the marketplace in forcing a rational resource policy. Over the long term, the marketplace forces substitutions and the use of lower-grade ores. But the marketplace has a high discount rate: in technological changes that require many years, the marketplace as it now operates invariably seeks out paths that optimize short-term advantage. Such paths may waste resources in the long run. The situation is well illustrated by the light water breeder reactor (LWBR) and the light water reactor (LWR). Over a 30-year period, a 1000 megawatt-electric LWR with no recycling requires about 5000 tons of uranium; an LWBR of the same size may require about 1500 tons of uranium. On the other hand, almost all of the LWBR inventory must be invested during the first few years, whereas the LWR uses its uranium rather uniformly over its lifetime. Thus if one judges the relative economic costs on a very short write-off, the LWR wins; if the write-off is 30 years or longer, the LWBR wins. From the viewpoint of husbanding resources, over the long term the LWBR is better than the LWR; over the short term LWR is better.

Recycling faces the same dilemma. How can one use the marketplace to encourage recycling when, in the short run, it pays not to recycle? Is it possible for the marketplace to be modified, perhaps by govern-

Table 7. Possible annual energy budget for demandite, avalloy, and agriculture in stage 3. All values are kilowatts per capita, unless otherwise noted. World values are taken as half of U.S. values for industry and equal to U.S. values for agriculture.

	United States		World	
	Present	Stage 3	Present	Stage 3
Population (× 10^6)	200	300	3600	10,000
Industry				
Avalloy*	0.60	1.20	0.15	0.60
Inorganic chemicals	0.86	1.12	0.13	0.56
Cement, stone, clay, and glass	0.21	0.27	0.08	0.14
Petroleum refining and petrochemicals	0.47		0.07	
Reduced carbon and hydrogen (petrochemicals)		0.24		0.12
Total demandite	2.14	2.83	0.43	1.42
Agriculture				
With desalted water		1.70		1.70
Without desalted water	0.87	0.87	0.68	0.87
Total, industry and agriculture (with desalted water in stage 3)	3.01	4.53	1.11	3.12
Total, all other uses	8	10.5	0.4	4.4
Total energy use	11†	15	1.5	7.5
Increase in stage 3				
Industry		0.69		0.98
Agriculture		0.83		1.02
Total		1.52		2.00

*Only new metal from ore is considered; total metal ≈ 1.5 times new metal. †The total in the United States in 1968 was 9.6 kw per person.

Table 8. Annual fuel and metal ore spoils today and in stages 2 and 3. At present, coal, oil, and gas are available; half of the coal is strip-mined and half is mined underground. At the peak of stage 1, oil and gas are gone; 80 percent of the coal is strip-mined and 20 percent is mined underground. In stage 2, strippable coal is gone and all coal is mined underground. In stage 3, all the coal is gone, all energy is from nonfossil fuel resources.

Period	Population (× 10^6)	Energy (kilowatts per person)	Spoils (tons per person)				Total annual spoils (× 10^6 tons)
			Coal	Breeders	Avalloy	Total	
			United States				
Stage 1							
Present	215	11	25		1.3	26.3	5.6
Peak	250	13	100		≈ 2	102	26
Stage 2	275	14	10		≈ 3	13	3.6
Stage 3	300	15		0.6	4	4.6	1.4
			World				
Stage 1							
Present	4,000	1.5	7		0.4	7.4	29.6
Peak	6,000	3	35		≈ 1	36	216
Stage 2	8,000	5	5		≈ 1.5	6.5	44
Stage 3	10,000	7.5		0.3	2	2.3	23

ment fiat, to reduce its discount rate, to take a longer, resource-dominated position?

Our technical message is clear: dwindling mineral resources in the aggregate, with the exception of reduced carbon and hydrogen, are per se unlikely to cause Malthusian catastrophe. But the exception is critically important; man must develop an alternative energy source. Moreover, the incentive to keep the price of prime energy as low as possible is immense. In the Age of Substitutability energy is the ultimate raw material. The living standard will almost surely depend primarily on the cost of prime energy. We therefore urge moving as vigorously as possible, not only to develop satisfactory inexhaustible energy sources the breeder, fusion, solar and geothermal power but to keep the program sufficiently broad so that we can determine, perhaps within 50 years, the cheapest inexhaustible energy source.

Our social message is less clear and certainly less optimistic. Although we see during the Age of Substitutability no insuperable technical bars to living a decent rather than a brutish life (assuming, of course, a stable population), whether in fact this will happen is far from certain. As Heilbroner (*19*) has pointed out, local shortages, which in the course of history are destined to be viewed as transitory, can and do cause large social and political instability. Heilbroner's "wars of redistribution," pitting the overpopulated have-nots against the underpopulated haves, could collapse society long before our carbon runs out. That the Age of Substitutability will, in principle, be autarkic, since mankind will no longer depend on reduced carbon (which is located in a few places), is little solace for governments or peoples today who look upon shortages of coming decades as threatening our entire social structure. We do not argue that the Age of Substitutability will be an easily achieved technological heaven-on-earth. Rather we urge attention to those institutional deficiencies that now prevent us from passing through stage 2 of our human voyage without causing the boat to capsize. The landfall, if we arrive at stage 3, should be surprisingly better than the catastrophists have predicted.

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11. A convenient small battery that does not use scarce materials and lasts a long time is an obvious target for research. However, if such a battery were never developed, we could revert to standard miniaturized dry cells (based on zinc and manganese) with only slight inconvenience. It must be remembered that in a 25-g cell used to power a portable computer, there are only 10 g of mercury. Even if the price of mercury rises 100-fold, the overall cost of the computer would rise by $12 if we elected to stay with the mercury battery instead of converting to shorter-lived, cheaper Zn-Mn dry cells. In the longer term, a substitute for the lead battery also may be needed.
12. Other examples of elements with finite resources that may have very high leverage are silver, which is used in photography; tungsten, in tool-making; lead and antimony, in storage batteries; beryllium, in beryllium-copper alloys; and perhaps manganese, in steel-making. More study is needed to identify other such critical situations.
13. J. C. Bravard, H. B. Flora II, C. Portal, *Energy Expenditures Associated with the Production and Recycle of Metals* (ORNL-NSF-EP-24, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1972).
14. Could we imagine charcoal from wood, used to reduce iron ore until 150 years ago, replacing coke today? Is this practical?
15. Even if copper is replaced by aluminum, the energy per ton of avalloy changes by less than 10 percent.
16. For example, see A. M. Weinberg and R. P. Hammond, *Am. Sci.* **58** (No. 4), 414 (1970).
17. A. M. Weinberg, *Bull. At. Sci.* **22**, 4 (December 1965).
18. ———, *Nucl. News* **14**, 33 (December 1971).
19. R. L. Heilbroner, *An Inquiry into the Human Prospect* (Norton, New York, 1974).

20. We wish to thank E. R. VanArtsdalen and G. Marland for their help in preparing the manuscript. Oak Ridge National Laboratory is operated by Union Carbide Corporation for the Energy Research and Development Administration. The Institute for Energy Analysis is operated by Oak Ridge Associated Universities for the Energy Research and Development Administration.

Chemicals from Coal

By-products of conversion of coal to clean fuels will offer new options to the maker of chemicals.

Arthur M. Squires

Coal maintained its historic role in the chemical industry until the close of World War II (*1*). By 1950, however, new procedures and new products were firmly established as prime opportunities for growth; to give examples, ammonia from methane, synthetic rubbers, polyethylene, and aromatic feedstocks from petroleum. The United States abandoned ammonia and methanol from coal in the mid-1950's. By now, the shift to petrochemicals is almost complete. The role of by-product coke ovens is greatly diminished: they supply only 10 percent of the U.S. benzene market and 2 percent of the phenol. Petrochemicals now take 10 percent of the U.S. oil and gas supply, and have expanded at 7 percent per year in recent years.

When and where will petrochemicals give way, as they eventually must, to a revival of chemicals from coal?

A return to coal will be slow. The historic shift to petrochemicals was fast not only because oil and especially gas (*2*) were often cheaper than coal but also because processing equipment for the cleaner, fluid fuels is far cheaper. The equipment can conveniently reach large rates of production from individual processing units (*3*). Historic coal conversions did not develop beyond unit sizes that are far too small to be congenial now. Much development effort lies before the question, When and where? A better question might be, What among many R & D opportunities can pay off soonest?

Chemicals as By-products

Coal chemicals were mostly by-products of two carbonization procedures, one to supply town gas (*4*), and another, coke for steelmaking. Even ammonia synthesis depended upon gasification of the coke by-product of town gas manufacture (*5*). Viewed broadly, petrochemicals are by-products of the production and delivery of gas and oil for use as fuels.

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One factor conducive to preeminence of petrochemicals has been the steady advance in throughputs of petroleum in refineries. Quantities of oil treated are now so large that even a constituent present in a minor amount can be plucked out and provided for chemical use at a cost no competition could meet.

Even after world production of oil flags, as it eventually must, flows of hydrocarbons that undergo some sort of processing will continue to increase. Most U.S. refineries convert well beyond 90 percent of domestic crude oil to products of high economic value, such as fuels for transport and home heating, lubricants, and chemical feedstocks. Refineries elsewhere, in general, convert much less of the crude oil to such materials, often only about 50 percent. The remainder is provided as heavy fuel oil to industry, including industry of the United States, which imports fuel oil. Revamping of refineries for further treatment of heavy oils will reinforce, for some time to come, the petroleum processor's advantage as a supplier of many chemical feedstock species.

Another factor that will extend the role of petrochemicals on the world scene is the impending development of gas resources of countries far from industrial populations. Such resources now provide tempting investment opportunities. Iran will ship gas to Europe via pipeline. Much gas will reach the United States in liquefied form (LNG). The United States is willing to import gas at around $3 per million British thermal units (1 Btu = 1.055×10^3 joules). This puts the value of gas almost anywhere in the world at around $1 per million Btu's as soon as s meone provides the large capital needed to build LNG plants and tankers.

Development of the gas resources of Venezuela, Nigeria, Indonesia, Saudi Arabia, Qatar, Abu Dhabi, Kuwait, and expecially Iran will enable these countries to dominate the world's supply of ammonia and methanol for decades. Ammonia already moves in world commerce in 50,000-ton tankers, and a 70,000-ton vessel is on the ways. Venezuela is shipping ammonia, and Arab commitments in petrochemicals exceed $20 billion, with more than $30 billion in projects under study (*6*). Proved reserves of natural gas in the Middle East are about 20 to 30 percent of the world's total (*6*). Iran is the giant: its proved reserves are already comparable to those of the United States, and probable resources are far greater, yet present production is but 5 percent that of the United States.

Existing technology for converting coal to ammonia or methanol cannot compete in much of the United States with conversion of natural gas to these chemicals in Venezuela, for example. Gas now being flared in that country could be converted to ammonia for sale in the United States at a price well below the cost of ammonia from coal (*7*). The Venezuelan ammonia would still be competitive if gas in Venezuela were valued at about $1.50 per million Btu's. This comparison takes into account a shipping cost of about $45 per ton. Gas in Venezuela could be valued at about $2 per million Btu's for conversion to methanol for the United States, taking into account a shipping cost of about $25 per ton.

No doubt it will be good policy to have some domestic ammonia and methanol synthesis to establish a domestic price and to ensure at least a partial supply. Some production from subbituminous coals of the West may even be economically competitive in local markets because of high costs to ship the imported chemicals over land.

By-products of Clean Fuels

These considerations lead to the view that early opportunities for chemicals from coal must be sought where coal is processed in very large amounts for other needs.

The projection of world oil production shown in Fig. 1 (*8*) suggests that the world market for heavy fuel oil may dry up soon. Indeed, the major oil companies of the world already have in hand the design studies for revamping refineries to convert heavy oil to lighter, more valuable products. Only specialists in methods of technological change can fully appreciate how alarmingly short the time is that remains before the world must make a major shift from oil to coal for its industrial energy needs (*10*).

It goes without saying that a return to coal must not recreate the "smoky Pittsburghs" of the past. The urgent R & D goals are processes for clean combustion of coal and its conversion to clean industrial fuels.

Such processes can provide the earliest R & D payoffs: they will be simpler and cheaper to develop and build, as well as higher in coal conversion efficiency, than processes for synthetic methane or gasoline. This is not to say the latter are not important, but as I pointed out before (*4*), the quickest way to capture significant supplies of "new" gas and oil is to convert existing boilers and furnaces to clean fuels from coal.

Which processes for clean fuels from coal can be realized the soonest? What chemical by-products might they yield?

Gasification with Steam and Oxygen

I do not see much play, at least soon, for complete gasification of coal by steam and oxygen. Costs are high, especially for gas cleaning. The Lurgi gravitating-bed gasifier (*4*), for example, makes a gas difficult to clean because of tars. Gas from the Koppers-Totzek system (*4*) contains much extremely fine dust. The latter system also faces a heavy cost for gas compression if the gas is required at pressure.

Complete gasification yields primarily H_2 and CO. The latter can be converted to hydrogen by the reaction

$$CO + H_2O = CO_2 + H_2$$

and scrubbing out CO_2. Partial conversion of CO to H_2 yields a synthesis gas for methanol

$$CO + 2H_2 = CH_3OH$$

Complete conversion to H_2 and addition of nitrogen yields a synthesis gas for ammonia

$$N_2 + 3H_2 = 2NH_3$$

The Office of Energy R & D Policy of NSF engaged Chem Systems, Inc. (*7*), to study chemicals from coal and identify R & D objectives worth pursuing. Chem Systems recommended work on systems for complete gasification that yield synthesis gas at high pressure. The gas should contain the least possible amount of methane, hence also, zero tar.

Chem Systems endorsed work in progress at the Pittsburgh Energy Research Center of ERDA on homologation of methanol by its reaction with synthesis gas to yield ethanol (*11*)

$$CH_3OH + CO + 2H_2 = C_2H_5OH + H_2O$$

The latter can be dehydrated readily to supply ethylene.

The Electric Power Research Institute is looking at the interface between systems for coal-based synthetic alcohols and electricity generation. An urgent need of the electricity industry is a clean liquid fuel to fire gas turbines used to meet peaks in demand for electricity. In past screenings of catalyst formulations for methanol synthesis, those that gave higher alcohols were passed over. Tailoring a catalyst for large yields of higher alcohols could give a gas turbine fuel while allowing some "creaming off" of methanol for sale as a chemical.

By Fischer-Tropsch synthesis and related syntheses, CO and H_2 can be convert-

ed to an astonishing variety of products (*12*): liquid fuels, lubricants, waxes, soaps, detergents, alcohols, aldehydes, and acids, and even fats reported to be similar in taste and nutritive value to natural butter (*13*). Many of the products were made on what was a large scale for the German economy of 1944.

South Africa has operated a Fischer-Tropsch plant for nearly 20 years, and has recently announced a nearly tenfold expansion from the present daily output of 4000 barrels of gasoline and a variety of chemicals. Australia has announced a plant of comparable size.

The thermal efficiency of Fischer-Tropsch synthesis, in practice, is below 50 percent; capital cost is high; and its development in South Africa and Australia is attractive because coals are available there at unusually low costs. Chem Systems (*7*) concluded that liquids from the synthesis, when conducted in gas- or liquid-fluidized beds of catalyst, are expensive feedstocks for cracking to ethylene in the United States. Ruhrchemie AG of West Germany, however, has worked to modify the synthesis in its fixed-bed reactor to afford increased yields of C_2 to C_4 olefins. On laboratory evidence, Schnur (*14*) projects a product running as high as 50 to 55 percent ethylene and propylene. Schnur believes that this product might represent an economic proposition at coal costs appreciably higher than those for the South African and Australian enterprises. The Ruhrchemie reactor, as it appears in the South African installation, is so small in scale as to be uncongenial to U.S. engineering thought, but it ought to be remembered that reactors contribute but a minor part of the total capital cost of a Fischer-Tropsch installation. Ruhrchemie is developing a larger fixed-bed reactor.

As improvements are made in coal gasification techniques, recurring reevaluation of Fischer-Tropsch synthesis would appear in order. The best opportunities may lie in approaches that yield a variety of products, including synthetic methane for sale to pipeline gas companies. Laboratory work on Fischer-Tropsch catalysts can be expected to increase yields of specific chemical products. In the long run, large supplies of synthesis gas are certain to appear in plants for converting coal to gasoline or synthetic natural gas. At the least, it may be anticipated that parasitic syntheses of chemicals will follow.

Partial Conversion of Coal

The need suggested by Fig. 1 is so urgent that development opportunities must be sought that offer the fewest hurdles. Proposals for advanced systems for complete gasification or liquefaction of coal face difficulties that could take much time. It is sensible to look closely at proposals for partial conversion of coal that ought to be easier and quicker to develop.

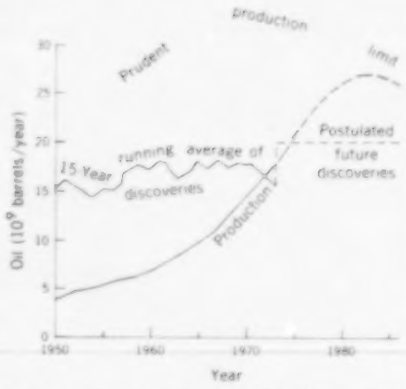

Fig. 1. Projection of oil production in non-Communist countries made by Warman (*8*) just before the Yom Kippur War. He reckoned annual discoveries of oil on basis of present knowledge of their size. Since production should not prudently exceed about 1/15 of reserves, collision between growing demand and declining production capability became inevitable when production topped the 15-year running average of discoveries, unless oil geologists could promptly step up discovery. The projection assumed future annual discovery at 20 billion barrels. Warman (*9*) estimates the current discovery rate at about 10 billion barrels. An offsetting factor is reduced growth in demand, caused by OPEC's increase in price as well as by economic recession.

Such proposals, of course, face the problem of marketing a by-product coke or char. This should not be too difficult, once everyone understands in his bones, as well as in his head, the difficult spot the world is in. There is sure to be a great expansion in combustion of coal. It might as well be coke or char. Burning these solid fuels in pulverized form presents no great problem if a fuel gas is furnished in relatively small amount to stabilize the flame. Availability of these fuels, however, will give the advantage to the new fluidized bed combustion systems (*15*).

Other things being equal, there will be an advantage for proposals that yield coke or char in form of relatively large particles, rather than as a fine dust. Special advantage will accrue to proposals that yield a coke low in sulfur. Availability of such coke in lump form could stimulate the production of fuel gas on a small scale in air-blown gas producers (*4*, *5*).

Some interesting possibilities would not yield a coke of sufficiently low sulfur content if practiced on the high-sulfur coals more common in the eastern part of the United States, but would yield such a coke from the low-sulfur coals typical of the West. These possibilities should be studied because bringing western coal East may be the best way to put many boilers and furnaces into compliance with sulfur dioxide emission standards. Commonwealth Edision Co. of Chicago is already burning about 9 million tons of Montana subbituminous coal per year, and eastward shipments of such coal are certain to increase. Their interception in plants to cream off a clean fuel gas or liquid could make good sense.

With a few exceptions, recent U.S. efforts have dealt with complete conversion of coal to a single product, and therefore multiproduct proposals have received less attention. There is room yet for invention. I offer the following discussion of several such proposals, some still in the laboratory, as much to illustrate as to direct attention to specific ideas.

Flash Pyrolysis

Occidental Research Corporation, is developing a process for flash pyrolysis of coal at atmospheric pressure (*16*). The coal would be heated almost instantaneously to about 925°C, and the residence time of vapor product at this temperature would be about 2 seconds. Working on a typical subbituminous coal of the West, the process could convert about 30 percent of the coal to a gas having a higher heating value, when dried, of about 630 Btu per cubic foot (1 standard cubic foot at 60°F and 1 atmosphere = 0.0268 normal cubic meter at 0°C and 1 atmosphere). The process yields about 10 percent tar, but Occidental proposes to recycle the tar, cracking it to extinction. The raw gas is rich in ethylene, and the process, if exploited on a large scale, could supply a significant fraction of U.S. demand for ethylene.

Char of 0.6 percent sulfur content would result from a typical Western subbituminous coal containing 0.83 percent sulfur. The char would meet the current legal requirement for fuel in the United States. An electric utility operating both coal-fired and gas- or oil-fired boilers might adopt flash pyrolysis to supply char to the former and gas to the latter, especially if the latter are expected to operate at a high load factor for a number of years.

Partial Gasification by Steam

A surprise of the Synthane development of the Pittsburgh Energy Research Center of ERDA was appearance of methane in gas at elevated pressure from steam-fluidized beds in amounts leading to calcu-

lation of equilibrium ratios near the top line of Fig. 2, which I published in 1961 (*17*). Lines A, B, and C in Fig. 2 had shown a downward trend in equilibrium ratio for steam-fluidized gasification of anthracite, cokes, and chars as pressure increased. I had supposed a similar downward trend would appear for gasification of raw coals of bituminous and lower rank. The new Synthane data (*18*) were for a lightly pretreated bituminous coal.

I hypothesized (*17*) that the equilibrium ratios of Fig. 2 reflect a quasi-equilibrium between hydrogen and the active carbon present in a steam-fluidized bed. Dent (*19, 20*) had pointed out that gasification kinetics in such beds are dominated by the fact of solid mixing, which brings frequent exposure of carbon to steam at high concentration near the bottom of the bed, reactivating the carbon. Gasification reactivity of an oven coke, that has soaked for many hours at more than 1000°C, is poor in a gravitating bed, yet is comparable in a fluidized bed to reactivity of anthracite or a char made at much lower temperature

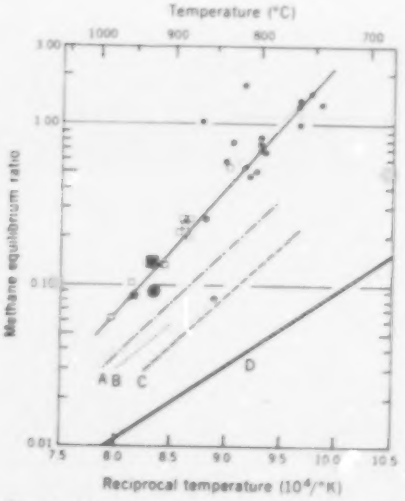

Fig. 2. Methane equilibrium ratios (*17, 18*), $y_{CH_4}/y_{H_2}{}^2P$, reckoned from composition of gases emerging from steam gasification of coals and chars in fluidized beds; y, mole fraction; P, pressure in atmospheres. ★ and □, A caking bituminous and a subbituminous coal, respectively, treated at atmospheric pressure. ●, Peat at atmospheric pressure. ■ and ●, Synthane pilot units at 25.5 and 40 atmospheres, respectively (711 and 102 mm in inside diameter, respectively). The top line is based on data where all carbon in volatile matter and, typically, about one-half of the fixed carbon were gasified. Line A represents atmospheric-pressure gasification of anthracite, cokes, and chars that were previously soaked in nitrogen for many hours at gasification temperature. Line B is for a bituminous char, also soaked in nitrogen, at 9.3 atmospheres. Line C is for anthracite at 12 to 17 atmospheres. Data for lines A, B, and C in general reflect gasification of more than 80 percent of the fixed carbon. Line D is thermodynamic equilibrium for graphite.

(*21*). Yields of methane during early stages of gasification of a fresh char (Fig. 3) (*17, 22*) tend to support my hypothesis with respect to Fig. 2. The early yields suggest that activity develops substantially to the level for continuous gasification of a raw bituminous coal and then declines. The percentage of carbon gasified is greater for lines A, B, and C of Fig. 2 than for the top line.

The credibility of the hypothesis is enhanced by data from a U.S. Bureau of Mines experiment on the reaction of Pittsburgh seam coal in a fixed bed with steam at 400 atmospheres (*23*). The coal was heated in flowing steam to 800°C in 2 minutes, and the coke was quenched directly thereafter. If it be assumed that substantially all gas was made in the second minute of the 2-minute heat-up time, one calculates a methane equilibrium ratio of 0.32 from the gas yield data. If it be assumed that substantially all gas came off in the last one-half minute, one gets 0.55. It might be noted that the gas, water-free, contained 39 percent methane. The calculated ratios compare with 0.75 from the top line of Fig. 2. It should be emphasized, however, that I would limit the hypothesis to steam-fluidized beds. There is no reason to expect Fig. 2 to correlate equilibrium ratios from fixed beds and dilute suspensions or from reaction of coals with hydrogen (*24*).

A commercially attractive operation can be visualized with essentially no extrapolation from known large-scale experimental facts. Figure 4 is a new concept for gasification of coal in a fast fluidized bed (*25*), with the advantage that reaction of steam and raw coal is conducted in a zone that is free of products of combustion. The concept takes advantage of the fast bed's relative freedom from the massive backmixing of gas that characterizes a slow, bubbling fluidized bed (*26*). Gas from the top of the steam-reaction zone ought to have a methane content approaching that indicated in the top line of Fig. 2. For operation at an elevated pressure, this gas will be a rich fuel gas. In the upper part of the vessel, the gas mixes with products of combustion of coke with oxygen that occurs in the annular space provided around the upper part of the steam-reaction zone.

A calculated example for Illinois bituminous coal uses a vessel 3.66 meters in inside diameter and 20 meters tall working at 20 atmospheres and 900°C. The velocity of the fluidizing gas is 3.66 meters per second. Coal feed is 8509 tons per day (1 short ton = 0.907 metric ton) on a moisture-and-ash-free basis, and the coke product is 4332 tons per day on the same basis. The percentage gasification of fixed carbon is less than that for most data on the top line

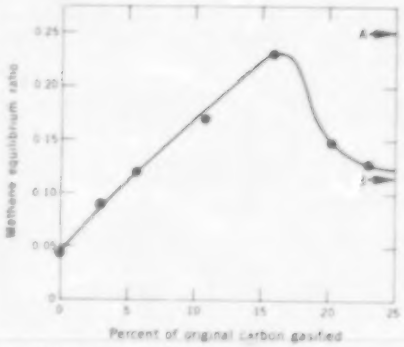

Fig. 3. Methane equilibrium ratios (*17, 22*) during early stages of gasification of a fresh bituminous char (never soaked at temperature in nitrogen) in a steam-fluidized bed at 871°C and atmospheric pressure. Arrow A points to equilibrium ratio for raw coal (top line of Fig. 2). Arrow B points to the ratio for chars previously soaked in nitrogen (dot-dash line of Fig. 2).

of Fig. 2. The fuel gas product has a higher heating value of 536 Btu per cubic foot after removal of water, sulfur species, and carbon dioxide. The product's total heat value amounts to 101,000 million Btu's per day, and so it could substitute for about 100 million cubic feet of natural gas per day or about 17,000 barrels of oil per day. Oxygen consumption is 1810 tons per day (*27*), and steam flow is 166.5 tons per hour (*28*).

Distributing Industrial Gas

Processes like Fig. 4 or like Occidental's flash pyrolysis could supply fuel gas attractive for distribution to industrial parks or industrialized regions extending for scores of miles. A process working at elevated pressure would have the advantage of reducing costs for gas compression. Costs for cleaning a gas at high pressure also are less, especially in the case of a [illegible] like that indicated in Fig. 4 where [illegible] conditions may be chosen to eliminate [illegible].

Candela's suggestion (*29*) that a regional system for industrial fuel gas might embrace the entire northeastern portion of the United States is worth examining. The system might be put together, at least in part, by preempting a portion of the present pipe network for distributing natural gas. The system would restore lost flexibility in fuel supply. It could provide fuel gas for peaking gas turbines as well as for combined cycle systems. It could provide fuel gas to retrofit old oil- or gas-fired boilers that have only a few years of remaining life or that operate at low load factor. Gas could be added to the system wherever it passes a coal field or a large customer for coke or char by-product.

Gas from the system could be re-formed

with steam at low capital cost to provide synthesis gas for ammonia or methanol. This is the best hope for domestic sources of these chemicals to compete with sources from countries like Venezuela and Iran. In the long run, the price of industrial gas from regional systems might govern the world price of these chemicals.

Flash Hydrogenation

Chem System's study for NSF (*7*) identified flash hydrogenation as an R & D objective that could lead to aromatic feedstocks of low cost as by-products of conversion of coal to synthetic natural gas. Flash hydrogenation is a variant of the Hydrane process under development for a number of years at the Pittsburgh Energy Research Center of ERDA (*30*). Coal would be heated rapidly in hydrogen at high pressure, and the vapor product of reaction would be quenched after a residence time at temperature of only seconds. The City College Clean Fuels Institute (*31*) has reported conversion of 10 percent of carbon in Illinois bituminous coal to benzene, 7 percent to ethane, and 14 percent to methane in experiments at 700°C, 100 atmospheres, and a vapor residence time of 3 seconds. Brookhaven National Laboratory (*32*) reported somewhat higher conversions of lignite to benzene. Ethane from flash hydrogenation could become an important source of ethylene.

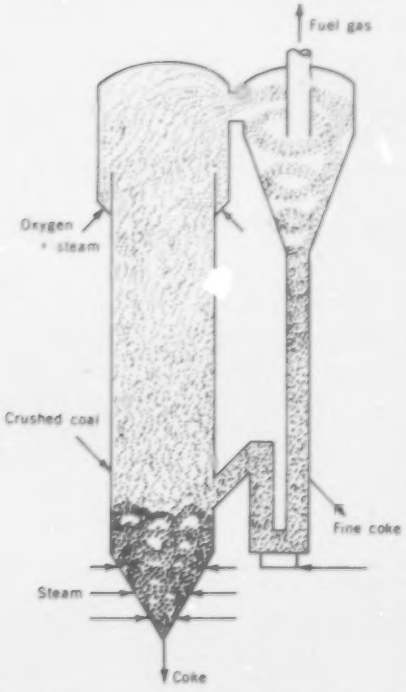

Fig. 4. New concept for partial gasification of coal by steam in a fast fluidized bed.

Supercritical Gas Extraction

Well known to producers of natural gas is the phenomenon of retrograde condensation, the condensation of the heavier hydrocarbon species present in the gas when its pressure is reduced. The opposite of this phenomenon may be termed "supercritical gas extraction," the vaporization of heavy molecules by a gas above its critical pressure. The equilibrium content of the heavy molecules in the "extract" is greatest if the critical temperature of the extracting gas is close to the temperature of the experiment. Great Britain's National Coal Board (NCB) (*33, 34*) has studied supercritical gas extraction of coal for a number of years.

To understand how extractable material can be present in coal, consider the reactions that occur when coal is heated slowly. Kirov and Stephens (*35*) provided insight into these reactions by subjecting a large number of Australian coals to parallel thermogravimetric, viscosimetric, calorimetric, and chloroform extraction experiments. These authors identified two chemical reactions that occur before coal decomposes to release appreciable quantities of gas and tar vapor.

"Reaction 1" occurs between about 250° and 300°C, and is evidenced by an endotherm amounting typically to a little under 0.2 kilocalorie per gram-atom of carbon in the coal. There is a decrease in the coal's acidity, and Kirov and Stephens speculated that reaction 1 involves the breaking of hydrogen bonds, since participation of a phenolic hydroxyl group in such a bond increases its acidity.

A second endotherm, typically about the same in magnitude as the first, announces "reaction 2" between about 340° and 400°C. There is an increase in phenolic oxygen, and Kirov and Stephens speculated that reaction 2 is a splitting of ether bonds,

$$R_1OR_2 = R_1O^{\cdot} + R_2$$

followed by transfer of nearby hydroaromatic hydrogen in the coal to satisfy the free valences and give

$$R_1OH + HR_2$$

They speculated that the ratio of hydroaromatic hydrogen to ether oxygen may be an important parameter for characterizing coals (*36*). Kirov and Stephens emphasize that both reactions 1 and 2 are rapid and appear to involve a tiny fraction of the chemical bonds in the coal.

Australian coals of lower and higher rank (below and above, respectively, about 85 percent carbon content) display distinctive behavior with respect to chemical decomposition and development of fluidity when heated at 3°C per minute. In both types of coal, reaction 1 is accompanied by only minor release of water vapor and alkyl aromatic species. After a coal of lower rank has been heated to 350°C and then cooled, it will release a larger extract to chloroform at 100°C than will unheated coal. Reaction 1, on the other hand, liberates little additional matter extractable by chloroform from a coal of higher rank.

In a bituminous coal, reaction 2 develops plasticity (*37, 38*). A coal of lower rank begins to decompose almost at once, and remains plastic over only a relatively small temperature interval as the coal is heated further at 3°C per minute. In a coal of higher rank, on the other hand, reaction 2 precedes significant releases of gas and tar vapor. Such a coal melts over a narrow temperature range, at the same time releasing material extractable by chloroform at 100°C. Typically, the viscosity of the fluid coal is about 1×10^4 poise. This remains nearly constant over a 30° to 40°C interval during subsequent slow heating. Onset of decomposition occurs well after melting. Later on, loss of fluidity occurs over a relatively narrow temperature range, a little ahead of the temperature at which the rate of decomposition is at a maximum.

NCB (*34*) reports that supercritical toluene at 350°C extracts 17 percent of a British 802 coal (such coal contains more than 36 percent volatile matter and is very weakly caking). Another report (*33*) suggests that yields up to 33 percent are obtained at about 400°C with fractions of coal tar or petroleum naphtha as extracting gas. Yields of gas and water are small. This is consistent with Kirov and Stephens' views concerning their reactions 1 and 2, and NCB appears justified in its conclusion that supercritical gas extracts have undergone little if any chemical degradation during their extraction. It might also be remarked that recombination or polymerization reactions, such as lead to the solidification of a fluid bituminous coal as it undergoes decomposition, probably play little if indeed any role in supercritical gas extraction at temperatures up to 400°C.

The extracting gas including extract has a low density and viscosity, making separation of undissolved char residue easy. Reduction to atmospheric pressure causes the coal extract to precipitate, allowing its separation from extracting gas.

I understand the separated extract to be a solid at normal temperature, but to melt below about 100°C. The NCB's toluene extract at 350°C contained 0.1 percent sulfur, and this suggests that an extract of many U.S. coals from the West might be sufficiently low in sulfur to find use as a utility fuel, attractive for retrofitting oil- and gas-

fired boilers as well as for firing gas turbines. Study of this opportunity would appear in order.

NCB (*33*) reports that the extract residue is a porous, nonagglomerating char. Extraction of high-volatile coals at 350°C should yield a char still containing a significant amount of volatile matter, an aid in pulverized fuel combustion. An incidental benefit for U.S. coals from the West would be removal of their typically high content of water.

About 20 percent of the toluene extract at 350°C was an oil soluble in petroleum ether, about 65 percent asphaltenes soluble in benzene, and the remainder "pre-asphaltenes" insoluble in benzene. The average molecular weight of the oil was about 300, that of asphaltenes, about 600 (*39*). Atom ratios of hydrogen to carbon were about 1.20 and 1.05, respectively.

Examination of the toluene extract by spectroscopic methods and gas chromatography revealed an aromatic skeleton of open chain structure. Substituted benzene units are strung together along with smaller numbers of naphthalene, dihydroanthracene, and other larger aromatic moieties. Biphenyl linkages, methylene and ether bridges, and hydroaromatic units bind the structure. Nearly all aromatic units carry methyl or higher alkyl groups.

Reduction in molecular weight could produce chemical feedstocks, especially benzene and a variety of alkyl benzenes. The NCB (*34*) pointed out that the open chain structure offers the prospect that this might be easily accomplished. Indeed, some processing of the extract might be necessary to replenish the extracting gas. If so, supercritical gas extraction of coal would almost inevitably become a supplier of by-product chemicals.

I should emphasize that supercritical gas extraction remains in the laboratory stage of its development. It awaits engineering study before its potential can be judged. I discuss it here, in part, to illustrate what may emerge if more thought is given to opportunities for partial conversion of coal to clean fuels.

Chemicals from Coal Tar

The glorious history of the coal tar industry's great service to mankind makes it sad for me to set down my belief that this industry faces a dim future. Chemicals derived from coal tar have always represented a small fraction of the total, a by-product of a by-product, as it were. I cannot conceive that new carbonization plants will be built simply to supply chemicals.

The future of coal tar depends upon the future of gas-making processes that yield tar, carbonization as a technique for providing liquid fuels, and operations to supply the steel industry with coke.

The Lurgi gravitating-bed pressure gas producer (*4*) may provide basis for a few plants to provide synthetic natural gas, although even this proposition has been thrown in doubt with realization that a Lurgi plant for 250 million cubic feet per day (about 0.4 percent of the current U.S. gas demand) will cost on the order of $1 billion. Major supplies of tar chemicals are not likely to arise from this source.

I see little future for carbonization as a technique for supplying liquid fuels. Tars are difficult and expensive to upgrade to synthetic petroleum or chemicals. They usually crack and deposit coke upon reheating for their supply to a catalytic hydrogenation; and, when a furnace cannot be used, the cold tar must be injected into a large flow of hot hydrogen just ahead of the catalyst. Conversion of tars to useful products entails large consumption of hydrogen. Attempts to develop catalysts that will convert anthracene to two molecules of toluene, for example, have not been successful (*40*). Phenanthrene has been converted catalytically to biphenyl, but only in small yield (*41*). Work toward such goals is worth continuing at the bench, but does not yet provide basis for commercial hopes.

Slot ovens for metallurgical coke are long-lived, and many ancient ovens are still in use. The steel industry for its expansion is apt to turn to new coke-making processes [for example (*42*)] more easily made acceptable environmentally and capable of processing a wider range of coals. Some new processes yield more benzene than conventional ovens, and Chem Systems (*7*) assumed that the steel industry will continue to supply about 10 percent of the benzene demand. A hazard to this assumption is the development of large shipments of steel from countries like Venezuela and Iran (*43*).

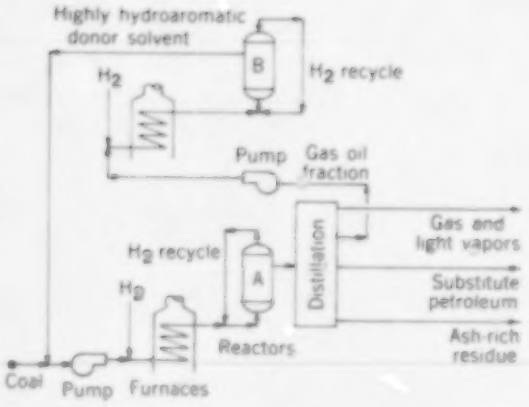

Fig. 5. Exxon's coal liquefaction process (highly schematic). Reactor A is noncatalytic. Reactor B contains catalyst and probably operates at higher pressure.

Coal Liquefaction

Direct liquefaction of coal is far from ready for use on a modern scale. A plant for 100,000 barrels of synthetic oil per day would need to process about 30,000 tons of coal per day. Germany's largest Bergius unit in World War II treated 600 tons per day, and the largest pilot unit now operating in the United States is for 50 tons per day. Most developments still work at a far smaller scale.

Most approaches liquefy coal through the agency of a donor solvent. Finely divided coal is slurried with an oil rich in polycylic species that contain both aromatic and hydroaromatic ring structures. When the slurry is heated to beyond about 400°C, the hydroaromatic rings of such species can release hydrogen. The aromatic rings that result from this release can be easily hydrogenated to restore the species' original capability of "donating" hydrogen to the coal. Tetralin (1,2,3,4-tetrahydronaphthalene) is an example of a donor solvent species. It is converted to naphthalene when it releases its four available hydrogen atoms.

Coal in the heated slurry reacts rapidly to release, in high yield, matter soluble in pyridine and benzene (pre-asphaltenes and asphaltenes, respectively) (*44*). The release of this matter occurs even if a donor solvent is not present (*45*), but in its absence, much of the matter polymerizes irreversibly to "coke" (*46*). The donor solvent's role, apparently, is to inhibit formation of coke by providing hydrogen to satisfy free valences that appear in the reacting coal substance.

With further time at temperature, the pre-asphaltenes and asphaltenes are converted by slower reactions to oils soluble in pentane.

Engineering approaches differ primarily in selection of location in the processing sequence at which the "spent," hydrogen-lean solvent is hydrogenated to restore its donor capability.

Current thinking in the United States is running against the Pott-Broche process approach, operated in Germany during World War II at the 100-ton-per-day scale. The coal-solvent slurry is pumped to a moderate pressure, 10 to 30 atmospheres, and held at about 425°C for an hour to dis-

solve about 75 percent of the coal. Dissolved material is separated from a solid residue, pumped to a higher pressure, and hydrogenated catalytically. A gas-oil fraction of the product is recycled to provide the donor solvent. In this approach, separation of unreacted coal and ash from reaction product is difficult.

Most U.S. efforts are elaborations of the Uhde approach, also operated in Germany. The slurry is pumped to a high pressure, typically 100 to 200 atmospheres; hydrogen is added; and the slurry is held at 425°C or beyond in presence of hydrogen to dissolve more than 90 percent of the coal. Hydrogen's role is apparently to restore at least part of the solvent's donor capability during the coal treatment, for it appears that the coal should contain ash matter having some catalytic virtue toward hydrogenation of the solvent.

Pittsburg & Midway Coal Company, a subsidiary of Gulf Oil Company, and, more recently, Southern Services Company and the Electric Power Research Institute have used the Uhde approach to produce a "solvent refined coal" that is low in sulfur and suitable for firing utility boilers and gas turbines. Hydrocarbon Research, Inc., a subsidiary of Dynalectron, the Pittsburgh Energy Research Center of ERDA, the Gulf Oil Co., and the Lummus Co. have modified the approach by adding a catalyst to the dissolution step to promote better hydrogenation of the solvent. These modified processes can operate to make a "refined coal" suitable for utility use, or at more severe conditions, such as 200 atmospheres and 455°C, to make a substitute petroleum.

In a further elaboration of the Uhde approach, Exxon (see Fig. 5) prepares a donor solvent by hydrogenating a synthetic gas oil under severe conditions. The solvent acquires a greater content of hydroaromatic carbon than has been used hitherto. Exxon's discovery is that the greater power of this solvent to donate hydrogen can convert coal in presence of hydrogen gas to a relatively light liquid. This can be distilled to provide both the synthetic gas oil for reuse and a petroleum substitute. Ash-rich residue from distillation is sufficiently small so that it can be disposed of by combustion or gasification. Exxon's approach has the advantage of avoiding a difficult filtration of ash residue from coal liquid.

Development of a coal liquefaction industry will eventually create opportunities for pulling out light aromatics and phenols. For the purpose of cracking to make ethylene, coal liquids are at a disadvantage with respect to the more aliphatic shale oils.

The Acetylene Alternative

Acetylene is a competitor for ethylene for making materials such as vinyl acetate, vinyl chloride, and acetaldehyde. Work has been in progress for many years on rapid pyrolysis of coal in a plasma arc at temperatures beyond 1400°C to make acetylene. Yields are of the order of 30 to 35 percent by weight of the coal, with 12 to 17 percent acetylene by volume in the gas leaving the pyrolysis reactor. There is a large recycle of hydrogen to the arc, and the process requires extensive equipment for acetylene recovery and gas purification. Operation is cyclic, since carbon tends to deposit in the reaction chamber, and frequent injections of steam are needed for its removal.

Chem Systems (7) believes that plasma arc processes have the potential of making acetylene competitive with ethylene, but they face large and difficult development tasks. Chem Systems assigned these a relatively low priority, since acetylene can substitute for ethylene in only about 17 percent of its uses.

Conclusion

For some time yet, chemicals will remain by-products of systems that supply natural gas, natural petroleum, and clean fuels from coal. The last-mentioned presents exciting near-term opportunities, especially in connection with clean fuels for industry that are so urgently needed. In the longer run, the world will be able to choose flexibly among gas, oil, and coal for supply of almost every fuel-based chemical.

References and Notes

1. Although ammonia from natural gas first appeared early in World War II, procurers of munitions deemed it prudent to build large plants synthesizing ammonia from gas made by gasifying coke in water-gas sets.
2. After World War II, development of pipelines made natural gas the cheapest industrial fuel in many parts of the United States, and gas displaced coal as a source of chemical process heat and often even as fuel to boilers for process steam. Coal held its place only in the manufacture of electricity, steel, and cement.
3. Sometimes a new petrochemical procedure could be taken directly from the laboratory bench to a commercial scale, and therefore many petrochemical engineers came to consider the pilot plant obsolete. Engineering education tended to deemphasize synthesis of engineering art and came to emphasize the analysis that would allow piloting on an ever smaller scale. Forgotten was how developers of historic coal conversions had struggled with problems of preparing, feeding, and processing coal; of withdrawing ash or coke; of purifying the gas or liquid product that was often contaminated by matter present in an amount so small as to remain undetected until it brought trouble in pilot operation. Some recent efforts in coal engineering have remained too long under analysis, delaying truths that only large pilot operations can reveal.
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5. Disappearance of gas coke removed a factor for flexibility in supply of clean fuel since air-blown producers (*4*) can easily convert coke to power gas.
6. D. C. Ion, *Availability of World Energy Resources* (Graham & Trotman, London, in press).
7. Chem Systems, Inc., New York City, "Chemicals from coal and shale: An R & D analysis for National Science Foundation," Rpt. PB 243,393 (National Technical Information Service, Springfield, Va., 1975). Chem Systems developed costs for methanol and ammonia on the scale of 1000 tons per day and used either the Koppers-Totzek gasification system (*4*) or a hypothetical improved system yielding gas under pressure. The capital for coal-based plant is more than double that for a plant based on gas.
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10. Will there be a world parallel of the recent economic dislocations in the United States brought on by shortages of natural gas? More than 50 percent of the expansion of U.S. energy supply between 1947 and 1972 was in form of gas. More than 50 percent of the expansion of world energy supply in recent decades was in form of petroleum. Figure 1 looks like the record for U.S. natural gas displaced about 10 years later in time. Although merger of intrastate and interstate markets for gas at the world price for energy from oil can alleviate immediate distress of industry in states (for example, New England) without gas production, curtailment in industrial use of gas is inevitable unless annual discoveries begin greatly to exceed the average over the past years. Many chemical plant furnaces were built so that they must be fired with a clean fuel. Two years ago, I expected operations to get under way to provide a clean fuel gas from coal (*4*). Instead, U.S. firms have preferred to buy propane or oil, even at OPEC's (Organization of Petroleum Exporting Countries) prices. Available devices for gasifying coal (*4*) are costly, take time to build, and convert coal at throughputs small in respect to many industrial needs. When supplies of fuel oil run short, however, the shift to coal will become inevitable.
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26. A. M. Squires, in *Future Energy Production: Heat and Mass Transfer Problems*, J. Hartnett, Ed. (Hemisphere, Washington, D.C., in press).
27. Oxygen requirement of the Koppers-Totzek system is more than 4000 tons per day for production of 101,000 million Btu's of gas per day at far lower heating value.
28. The concept of Fig. 4 is also attractive with substitution of air for steam and oxygen to the annular combustion space. A gas at a heating value approaching 225 Btu per cubic foot can be made at 20 atmospheres, a remarkable figure for an air-blown gasifier. I should note that the fast fluidized bed is also well suited for "moving burden" gasification, in which heat of reaction is supplied by circulating hot solid from a combustion zone [J. W. R. Rayner, *J. Inst. Fuel* **25**, 50 (1952); M. E. Sacks and R. T. Eddinger, in *Coal Processing Technology* (American Institute of Chemical Engineers, New York, 1975), vol. 2, p. 94]. I prefer the simpler arrangement of Fig. 4 as quicker to develop, recognizing that improvements can follow.
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46. It is tempting to associate Kirov and Stephens' reaction 2 with the release of soluble matter, also, to associate its subsequent conversion to coke in absence of a donor solvent with the solidification of a fluid bituminous coal as it undergoes slow heating. Coals of lower rank are harder to liquefy, and this fact may reflect chemical disparities that also underlie differences in behavior of coals of low and high rank as they undergo pyrolysis (*37*).
47. Work on the fast fluidized bed and flash hydrogenation of coal at The City College is supported by grant AER-72-03426 A (formerly GI-34256) from the RANN Program (Research Applied to National Needs) of NSF. For informative discussions, I thank M. Sherwin of Chem Systems, Inc., I. Topper of the Office of Energy R & D Policy of the NSF, and S. B. Alpert, R. H. Wolk, and W. C. Rivoski of the Electric Power Research Institute.

Thermochemical Hydrogen Generation

Thermochemical hydrogen could play an expanding role in future energy and chemical feedstock needs.

R. H. Wentorf, Jr., and R. E. Hanneman

Hydrogen has been discussed increasingly in recent years (*1*) as a potential, highly flexible energy medium of the future because it is ecologically attractive and broadly usable, it is easily stored and transported, and it can be produced from a virtually inexhaustible feedstock, that is, water. Hydrogen is currently a major industrial chemical serving primarily as a chemical intermediate in the production of hydrogen-containing substances such as ammonia, methanol, and refined petroleum products. The total world consumption of hydrogen presently exceeds 10^{10} kilograms annually (*2*).

The most important single barrier to new large-scale uses of hydrogen during the next several years appears to be cost—the price must be competitive with alternate, clean energy media. Most of the hydrogen produced currently in the United States and Europe is made by the steam reforming of natural gas or by the partial oxidation of oil, but decreasing petroleum reserves in the next decade may make it necessary to adopt alternative methods of generation. The major candidate technologies for this century include electrolysis, new open-cycle thermochemical processes based on fossil fuel feedstocks, and closed-cycle thermochemical generation methods. Longer range possibilities include biological and photolytic methods.

Electrolysis is the best developed of these technologies at present. Cost estimates for hydrogen production by the above methods indicate that, although electrolysis is more expensive than the best present open-cycle methods, it will become increasingly competitive later in this century. For smaller scale industrial uses and where high purity is important, hydrogen generated by on-site electrolysis will become a strong competitor with liquid or gaseous hydrogen delivered by truck.

Open-cycle thermochemical hydrogen generation processes are ideally based on the use of hydrocarbons, water, and heat, yielding carbon dioxide and degraded heat (lower temperature heat), in addition to hydrogen. Demonstrated and presently used open-cycle methods of producing hydrogen or hydrogen-rich gas include the reforming of natural gas, petroleum naphthas, or related intermediates under moderate pressures and the partial oxidation of various fluid hydrocarbons (*3*).

The abundance and lower long-term costs of coal have spurred interest in its use to generate hydrogen from water. Three major types of approaches include: (i) reforming methods with coal, steam, and catalysts; (ii) the use of intermediate metal-metal oxide methods, such as the steam-iron–iron oxide–coal system (*4*); and (iii) variations of high-temperature $O^{=}$ membrane systems (*5–7*).

Oxygen solid electrolyte membrane processes currently under evaluation in our laboratory offer the potential for cheaper

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production of hydrogen than by conventional electrolysis. In the simplified version shown in Fig. 1, coal char is burned to produce CO, and the heat developed is used to vaporize water. The water and CO are then passed over opposite sides of a hot, mixed-conduction solid electrolyte that conducts equally by electrons and by $O^{=}$. This results in the oxidation of the CO to CO_2, which is discarded, and the reduction of the resultant steam to H_2 under pressure. Countercurrent flow designs of the process depicted in Fig. 1 will tend to be preferred. In other versions of this process electrodes can be added and the electrolyte modified to provide partial electrical assistance to the water decomposition process (5, 7). Further technical advances of the better open-cycle thermochemical processes should permit overall thermal efficiencies of 60 to 70 percent for large plants producing H_2 from coal and water.

Continuing changes in ecological limitations and in fossil fuel prices, however, will tend to make open-cycle processes less competitive than other processes in the long term. Closed-cycle processes have been the focus of markedly increased research effort in the past few years. Our primary purpose in this article is to describe some new closed-cycle thermochemical processes for hydrogen generation and some of the underlying concepts used in their selection. The economic outlook for such closed-cycle thermochemical processes will be compared with that of open-cycle thermochemical and electrolytic methods.

Closed-Cycle Thermochemical Processes: Criteria for Process Selection

In closed-cycle thermochemical processes for hydrogen generation, ideally water and heat are the input ingredients and only hydrogen, oxygen, and degraded heat are the products. Several intermediate chemical steps and other recycled chemical species are necessary to accomplish this result.

In principle, thousands of combinations of multicomponent closed-cycle chemical systems exist that might yield a workable water-splitting process. In order to select the most promising cycles, it is useful to set up a series of criteria for the screening of potential candidate processes. These criteria include the thermal efficiency based on both thermodynamic and kinetic factors, the required maximum temperature of the process and its compatibility with various nuclear reactor or other heat sources, the compatibility of materials, their availability and cost, the apparent system complexity, and ecological or safety constraints.

A high thermal efficiency is desirable for both ecological and economic reasons: less heat is thrown into the environment, and the overall process cost is reduced because the cost of the input heat is a major item. Closed-cycle thermochemical water-splitting processes are Carnot-limited in a thermodynamic sense. The thermodynamic process efficiency, η^*, can be defined on the basis of the Gibbs free energy, or available work, as

$$\eta^* = \frac{T_M - T_m}{T_M}\,\beta\,\frac{\Delta G_f}{Q} \qquad (1)$$

where ΔG_f is the Gibbs free energy change associated with the formation of 1 mole of water under conditions where the hydrogen and oxygen are subsequently used (for example, 298°K and 1 atm); Q is the total heat required by the overall process to split 1 mole of water into hydrogen and oxygen; T_M is the maximum absolute temperature of the process; T_m is the minimum absolute temperature occurring in the process; and β is a factor (< 1) which includes energy and entropy losses due to: (i) fundamental heat imbalances from net exothermic reactions occurring at temperatures below endothermic ones, (ii) the operation of reactions at nonequilibrium conditions, and (iii) operating energy requirements such as those involved in pumping, separation steps, and heat losses from the plant. In potentially useful or competitive multistep cycles, β is expected to lie in the range of 0.3 to 0.7. In order to increase reaction rates and reduce unit capital and operating costs, processes will frequently be operated with a considerable displacement from equilibrium.

Equation 1 tells us that η^* increases with the maximum temperature used in the process. An upper limit of 1200°K appears to be realistic, as this represents the highest commercial nuclear reactor coolant temperature expected in the next one to two decades. Furthermore, corrosion and materials problems are more severe at higher temperatures. When the heat transfer between the nuclear reactor and the chemical process involves no phase change (as by condensing a vapor), the heat is carried as sensible heat (that is, the heat capacity multiplied by the temperature difference), and, in order to extract this heat, the temperature of the medium must fall but naturally not below the required chemical reaction temperature. An additional temperature drop is encountered in a heat exchanger. Furthermore, the temperature of the coolant must not be too high when it reenters the reactor in order to avoid materials problems or high circulation power consumption; if only the high-temperature chemical reactions require heat, then the necessary coolant temperature drop could be usefully realized by producing steam for electrical power. We consider a temperature of about 300°K as a lower limit for practical system operation and reaction rates.

Another useful type of process efficiency which has been used by various workers could be called the thermal yield efficiency, ϵ. It is based upon heat efficiency rather than work efficiency and is given by:

$$\epsilon = \frac{\Delta H_f}{Q} \qquad (2)$$

where ΔH_f is the heat of formation (or combustion) of a mole of water from hydrogen and oxygen. The quantity ϵ will always be slightly larger than η^* since the enthalpy of formation of water is larger than the Gibbs free energy of formation (at 298°K, ΔG_f = −56.69 kilocalories per mole and ΔH_f = −68.32 kcal per mole of liquid water) (8, 9).

The free energy of dissociation of water ranges from about 57 kcal/mole at 273°K to 44 kcal/mole at 1200°K. Thus, the equilibrium constant for thermal dissociation ranges from 10^{-43} at 273°K to about 10^{-9} at 1200°K and can be neglected. It is not feasible to dissociate water thermally in one step. However, the decomposition can be carried out in several chemical steps, each operating at its optimum temperature, with the recycling of all products except hydrogen and oxygen.

One thermodynamic criterion that must be met is that the sum of the standard enthalpies of reaction of the individual steps, $\Sigma \Delta H^\circ$, must equal or exceed about 68 kcal/mole for an overall dissociation of 1 mole of liquid water (or 57.8 kcal/mole relative to steam input). This value is nearly independent of temperature over the temperature range of interest for a given standard state (that is, −57.79 kcal/mole at 298°K and −59.52 kcal/mole at 1200°K) (8).

A second, less stringent thermodynamic criterion is that the standard free energy changes (ΔG°) for each of the separate steps (at their operating temperatures and pressures) be negative or close enough to zero to provide reasonable concentrations of products. For a reaction $r_1R_1 + r_2R_2 + \ldots \rightarrow p_1P_1 + p_2P_2 + \ldots$, where r_i moles of R_i plus r_2 moles of R_2 react to yield p_1 moles of P_1 and p_2 moles of P_2, one can use the well-known equation:

$$\Delta G^\circ = -RT \ln \frac{[P_1]^{p_1} \cdot [P_2]^{p_2} \cdots}{[R_1]^{r_1} \cdot [R_2]^{r_2} \cdots}$$

where R is the gas constant; T is the absolute temperature; and $[P_i]$ and $[R_i]$ are the equilibrium activities of species P_i and R_i, respectively, relative to the standard state for which ΔG° is calculated. The values of p_i and r_i affect the departure of ΔG° from zero which will provide reasonable concen-

trations of products. If the p_i for the desired product is unity, then at about 1000°K ΔG° should not be greater than about 8 kcal for a 2 percent concentration of desired product; higher values of p_i or continuous extraction of products from the reaction site may permit higher positive values for ΔG°. Large negative values for ΔG° generally imply excessive product stability which would cause difficulties in other steps of the cycle.

Practical considerations indicate that the number of reaction steps will be at least three. This can be seen as follows, with the representative set of reactions

$$\begin{aligned} &A + H_2O \rightarrow AO + H_2 && \text{at } T_1 \\ &AO + B \rightarrow AB + \tfrac{1}{2}O_2 && \text{at } T_2 \\ &AB \rightarrow A + B && \text{at } T_3 \end{aligned}$$

Let us assume as an approximate limit that ΔG° for each reaction is zero at the temperatures involved, which range between 300° and 1200°K. If, for example, two of the reactions were to take place at 300°K, the ΔG° of the other reaction must change by 56.7 kcal upon going from 300° to 1200°K. The standard entropy change for the reaction, ΔS°, is given by:

$$\left[\frac{\partial (\Delta G^\circ)}{\partial T}\right]_p = -\Delta S^\circ$$

(where the subscript p signifies constant pressure) and hence for a temperature difference of 900°K the value of ΔS° is 56,700/900 = 62.8 cal °K^{-1} mole^{-1} for the reaction per mole of hydrogen in the system. Such a large standard entropy change is rarely found. On the other hand, if the 56.7 kcal of ΔG° were to be divided equally between two reactions, each operating at 1200°K, the maximum allowed temperature, then the required ΔS° per reaction is 31.4 cal °K^{-1} mole^{-1}, which is not so unusual.

Applying Eq. 1 to the temperature limits described here, one can roughly estimate the minimum heat input to a closed-cycle process. Specifically, (1200° − 300°)/1200° = 0.75 = (56.7)/Q, or Q = 75.5 kcal is the minimum theoretical heat input to the process; this input ideally occurs at 1200°K to satisfy endothermic reactions. For two idealized and complementary reactions at 1200°K, each having $\Delta G^\circ = 0$ and ΔS° = 31.4 cal °K^{-1} mole^{-1}, and a limit of $\beta = 1$, one finds ΔH° for each to be about 37.7 kcal, endothermic. So when ΔS° is divided between the two reactions, the required heat input is ideally divided in the same ratio.

Since 75.5 kcal is supplied but the sum of all the ΔH° is 68.3 kcal, one concludes that the low-temperature reaction is exothermic by 7.2 kcal in this ideal case with no system losses. If the low-temperature reaction is more exothermic, then the extra heat must be supplied at higher temperatures. If all the high-temperature reactions do not occur at the maximum temperature, then the thermal efficiency is reduced, more heat must be supplied and more must be rejected to the environment at 300°K.

The above considerations also apply to cycles composed of n chemical steps. At least one step must be carried out at relatively low temperature, and the required ΔS° and ΔH° may be divided among $n - 1$ or fewer steps in many ways, depending upon the chemical reactions involved. However, practical and economic considerations appear to limit the number of steps to no more than eight.

Several separation or regeneration steps for intermediate products and reactants are generally required in closed-cycle thermochemical processes. Such separation techniques include mechanical, electrical, magnetic, condensation, adsorption, nonequilibrium quenching, precipitation, distillation, selective membrane diffusion, and other methods. It is important that the separation methods do not require substantial energy penalties. Movement of a product phase from one temperature to another temperature for a subsequent reaction must also be accounted for in the overall enthalpy balance.

In all potentially viable thermochemical processes it appears that a change in the oxidation state of one or more chemical elements (either anion or cation) will be a necessary requirement. The primary candidate elements for anions include sulfur, chlorine, bromine, iodine, and possibly nitrogen and phosphorus. Primary candidate elements for cations include iron, nickel, cobalt, manganese, copper, vanadium, and other transition and multivalent metals or complexes.

Some processes may be deterred from further consideration on the basis of high heats of reaction which limit the overall thermal efficiency to a relatively low value. For example, processes can be devised in which a sulfate undergoes decomposition to produce a metal oxide, SO_2, and O_2. However, such decompositions require so much heat at high temperatures that, even if all the other steps in the process require no heat, the overall thermal efficiency is seriously limited. For example, the evolution of $\frac{1}{2}O_2$ from $CuSO_4$ or $FeSO_4$ at 1000°K requires enthalpy inputs of 72.9 and 102 kcal/mole, respectively, for this step alone (*8*).

In devising processes, one can begin by considering all reactions which yield H_2 and O_2 from readily available materials with acceptable enthalpy changes and then try to fit them together in some way so that no by-products are left over. This can be done with the aid of a computer if sufficiently reliable thermodynamic data are available, but it is equally fruitful to review the chemical literature while keeping certain ideas in mind, such as the meshing of sets of reactions, their completeness, and their suitability for large-scale operation. After a set of promising reactions has been selected for a process, the reactions need to be studied in the laboratory to decide about the degrees of completeness and the rates. Tests also will be needed to determine the nature of a reaction in terms of the heat and material fluxes and the physical states of the products. For example, the formation of a glassy, sticky solid product would make the reaction difficult to use on a large scale.

After the suitability of the reactions has been ascertained, flow charts can be made. It is difficult to estimate the thermal efficiency of a process without constructing a flow chart to see how heat is to be best provided and rejected in the various steps and how products are to be separated. If all still looks favorable on both technical and economic grounds, more detailed studies of key reactions will need to be made and a small pilot plant will need to be constructed and operated.

Using the concepts and methods described above, we have devised one dozen closed-cycle thermochemical processes. Many other thermochemical processes have been proposed in other laboratories (*10*). Three of our processes, processes A, B, and C, are described below, each suitable for a particular range of maximum temperatures. The thermodynamic data used in these studies were drawn from standard references (*8, 9*). We found comprehensive chemistry texts such as those by Sidgwick (*11*) or Gmelin (*12*) helpful in the selection of reactions and processes based on the criteria outlined above. We have carried out experimental work on most of the reactions given in these processes, confirming that they proceed to an acceptable degree.

Process A

In this process hydrogen, oxygen, iron, chlorine, and magnesium atoms are cycled through the following steps (see Table 1):

$$3FeCl_2\,(c) + 4H_2O\,(g) \rightarrow Fe_3O_4\,(c) + 6HCl\,(g) + H_2\,(g) \qquad (A1)$$

$$Fe_3O_4\,(c) + 8HCl\,(aq) \rightarrow FeCl_2\,(aq) + 2FeCl_3\,(aq) + 4H_2O\,(l) \qquad (A2)$$

$$2FeCl_3\,(c) \rightarrow 2FeCl_2\,(c) + Cl_2\,(g) \qquad (A3)$$

$$Cl_2\,(g) + Mg(OH)_2\,(aq) \xrightarrow{\text{Cu}^{++}} MgCl_2\,(aq) + \tfrac{1}{2}O_2\,(g) + H_2O\,(l) \qquad (A4)$$

Table 1. Thermochemical data for process A

Step	Reaction temperature (°C)	Energies (kcal) for reactions as written	
		ΔH°	ΔG°
A1	450° to 900°	78 to 68	30 to −5
A2	50° to 110°	50	−1 to 7
A3	300°	28	4
A4	50° to 90°	38	−42 to −48
A5	350°	4	8

$$MgCl_2(c) + 2H_2O(g) \rightarrow Mg(OH)_2(c) + 2HCl(g) \qquad (A5)$$

This process can operate at relatively low temperatures if necessary, which limits the thermal efficiency by comparison with processes for which heat is available at higher temperatures. On the other hand, at lower temperatures, cheaper heat, such as solar energy or lower temperature nuclear heat rejected from another coupled process, can be used, and corrosion problems are less severe.

In practice, the indicated reactions are to be carried out as continuous processes and the reactions may not go to equilibrium. Various separations are required, and the overall efficiency of the process depends on how they are carried out. Let us now consider each of the above steps in more detail.

Step A1. Steam passes over solid $FeCl_2$ at 450° to 900°C (depending upon the heat source), and magnetite (Fe_3O_4), HCl, and H_2 are the products. If the temperature is slightly lower, the main products appear to be $Fe(OH)_2$ and HCl. The estimated enthalpy change at 450°C is about 78 kcal (or 68 kcal at 900°C) per mole of H_2, endothermic, based on the steam feed described below. The great stability of Fe_3O_4 prevents the oxidation reaction from proceeding completely to the Fe^{+3} state, and thus some Fe^{+2} is recycled without contributing to H_2 formation.

In one version of the reaction procedure, superheated $FeCl_2$ solution is fed to a heated rotating drum and allowed to flash to yield small particles for a large reaction surface. Magnetite beads could be used to assist stirring and heat transfer. The outgoing Fe_3O_4 gives up its heat to incoming feed. The outgoing H_2O and HCl are condensed to acid and thereby provide heat to some other stream; the condensed acid reacts with Fe_3O_4. The sour H_2 is scrubbed with Fe_3O_4 and water before being compressed for shipment or storage.

Step A2. The Fe_3O_4 from step A1 gives up its heat to the solution supplied to step A1 and then is dissolved in aqueous HCl at 50° to 100°C to form $FeCl_2$ and $FeCl_3$. Part of the HCl comes from step A1 and part from step A5. The dissolution is exothermic with 50 kcal liberated per mole of Fe_3O_4, enough to boil all the water formed in the reaction. The heat can be used in other endothermic steps, such as water preheating and steam generation for step A1.

In the presence of excess HCl, the $FeCl_3$ can be extracted with diethyl or di-isopropyl ether at 25° to 30°C. Very little $FeCl_2$ dissolves in the ether phase. The ether is evaporated and recycled. The $FeCl_2$ solution, after being stripped of ether and HCl, is fed into step A1. The ether solution of $FeCl_3$ contains some water and HCl which must be removed to produce dry $FeCl_3$ for step A3. The drying of 2 moles of $FeCl_3$ theoretically requires 62 kcal; this can be supplied by the heat of solution of less than 4 moles of HCl from step A1. Most of the ether can be evaporated at less than 50°C where abundant heat is available; in addition, step A4, described below, can supply 10 kcal at 50° to 90°C.

Step A3. This reaction takes place at around 300°C. It is possible to have liquid or solid $FeCl_3$ in equilibrium with solid $FeCl_2$ and Cl_2 vapor by changing the temperature slightly. At 1 atm, the melting point of $FeCl_3$ is 282°C and the boiling point is 315°C. According to Ringwald (*13*), the equilibrium ratio of Cl_2 to Fe_2Cl_6 vapor at 287°C is about 0.083; the ratio falls with increasing temperature because of the rapid rise of the vapor pressure of Fe_2Cl_6, and reaches 0.064 at 302°C. The heat of dissociation from solid $FeCl_3$ is about 26 kcal per mole of Cl_2; from liquid $FeCl_3$ the heat required is only about 5 to 6 kcal per mole of Cl_2, owing to the large heat of fusion of $FeCl_3$. The vaporization of a mole of solid $FeCl_3$ requires about 34.5 kcal of heat.

One way to carry out the reaction is to operate where $FeCl_3$ is liquid and to separate the solid product $FeCl_2$ from the liquid while condensing liquid $FeCl_3$ from the vapor mixture of Cl_2 and Fe_2Cl_6 at a slightly higher pressure. Traces of water hydrolyze the $FeCl_3$ to oxide or oxychloride which separates as a solid with the $FeCl_2$. The HCl leaves with the Cl_2 and forms $MgCl_2$ with the $Mg(OH)_2$ fed to step A4. Thus the presence of water in step A3 decreases the overall efficiency of the process.

Step A4. The absorption of Cl_2 by aqueous $Mg(OH)_2$ produces hypochlorite early in the reaction sequence. A basic hydrated cobaltic oxide, which forms if a cobalt salt is added to the mixture, catalyzes the decomposition of hypochlorite to O_2 and Cl^- (*14*). The Co^{+3} circulates with the Mg^{+2}; Ni may be used in place of Co. In laboratory tests the rate of O_2 evolution appeared to be limited by the dissolution rate of Cl_2.

At 25°C, step A4 is estimated to liberate about 38 kcal per mole of $MgCl_2$ formed in dilute aqueous solution, but the heat liberated will be less if less water is present, down to a minimum of 10.5 kcal if $MgCl_2 \cdot H_2O$ forms; we assume this latter situation for heat estimates.

Step A5. The hydrolysis of $MgCl_2$ is a well-known reaction used in times past for HCl and Cl_2 manufacture. Other possible products are MgO and MgOHCl. MgOHCl readily reacts with steam above 300°C and loses its chloride as HCl; MgO has both a strong physical and a strong chemical affinity for water. The water pressure at equilibrium at 350°C over $Mg(OH)_2$, calculated from standard data (*9*), is about 19 atm, and the heat of hydration is about 9 kcal/mole. However, the physical states of the $Mg(OH)_2$ and MgO affect the water content. In succeeding reactions it matters little whether MgO or $Mg(OH)_2$, or both, are present, and to describe the process we have simply used $Mg(OH)_2$.

Part of the feed for step A5 is the concentrated, essentially oxygen-free $MgCl_2$ solution from step A4; for energy balance purposes we assume it has the composition $MgCl_2 \cdot H_2O$. A mole of water, destined to be split, is also fed here as steam.

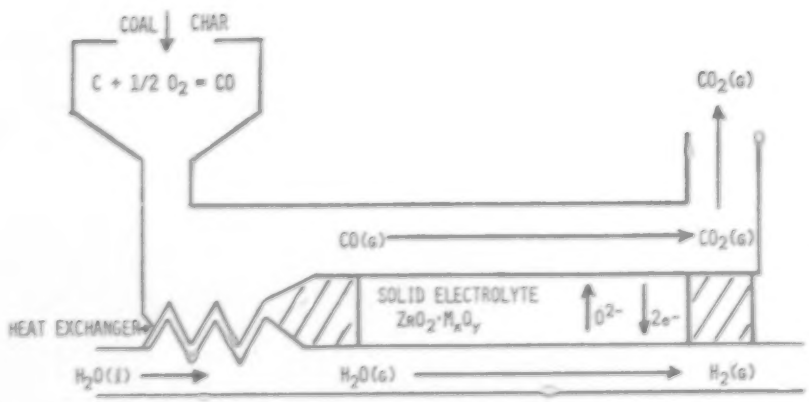

Fig. 1. Solid-membrane, open-cycle hydrogen generation process.

It is to be fed countercurrent to the $MgCl_2$ for greater conversion to HCl. If we assume it fed as steam at 350°C, the heat requirement for step A5 is about 24 kcal. However, initially the mole of H_2O is liquid; surplus heat is available at 100°C to vaporize it, but an extra 2.5 kcal will be needed to bring it to 350°C. Thus the total heat requirement for step A5 is about 26.5 kcal.

Another way to form O_2 from Cl_2 and water vapor is to use the reverse of the well-known Deacon process: $Cl_2 + H_2O \rightarrow 2HCl + \frac{1}{2}O_2$. This reaction is also catalyzed by a number of heavy metal salts such as those of copper, iron, nickel, or cobalt. This reaction runs well at high temperatures, for example 650°C, where one must solve the practical problems of separating O_2 from a hot, corrosive gas mixture.

The solution and dehydration of various chlorides in this process involve moderate amounts of heat at low temperature. Without detailed experimental data on each of these steps, the exact heat requirements for the entire process are difficult to calculate. However, if we assume that these steps are in approximate thermal balance, then most of the heat required in process A is used at 300°, 350°, and 450° to 900°C in steps A3, A5, and A1, respectively; the total heat requirement for these steps is about 133 ± 5 kcal per mole of H_2 formed. About 53 kcal is liberated at about 50° to 100°C in steps A2 and A4. The difference is 80.5 kcal, larger than the heat of formation of liquid water, 68.3 kcal, because not all the heat released at lower temperatures can be used. In addition to the ~ 133 kcal for heats of reaction, more heat will be needed for supplying pumping power and to make up for miscellaneous losses. By analogy with other industrial chemical processes, this extra heat requirement is estimated to be a minimum of 15 kcal per mole of H_2. For example, about 5 to 10 percent of the input of an oil refinery is used for such functions.

The overall thermal yield efficiency of the plant ϵ, assuming that the product H_2 is converted to water vapor, then would be $57.8/148 = 0.39$; that is, 39 percent of the input heat is available as hydrogen fuel [lower heating value (LHV)]. The limiting Carnot efficiency for the temperature interval 723° to 300°K, for example, would be $423°/723° = 0.586$ even if $\beta = 1$, but one must consider this using the free energy of formation of water vapor. Since 54.6 kcal of work is available from $H_2 + \frac{1}{2}O_2$ in a perfect fuel cell, the work efficiency is $54.6/148 = 0.37$. For this example, the value of β given in Eq. 1 is ~ 0.63. A simplified flow chart for process A is shown in Fig. 2.

Process B

In this process copper, chlorine, hydrogen, and oxygen atoms are cycled through the following basic steps (see Table 2):

$$2Cu(c) + 2HCl(aq) \rightarrow 2CuCl(c) + H_2(g) \quad (B1)$$

$$4CuCl(c) \rightarrow 2CuCl_2(c) + 2Cu(c) \quad (B2)$$

$$2CuCl_2(c) \rightarrow 2CuCl(c) + Cl_2(g) \quad (B3)$$

$$Cl_2(g) + Mg(OH)_2(aq) \rightarrow MgCl_2(aq) + H_2O(l) + \tfrac{1}{2}O_2(g) \quad (B4)$$

$$MgCl_2(c) + 2H_2O(g) \rightarrow Mg(OH)_2(c) + 2HCl(g) \quad (B5)$$

The last two steps are the same as the last two steps in process A. Their advantage is that they proceed at relatively low temperatures where the equilibrium favors the production of O_2.

Step B1. This reaction is conveniently carried out in aqueous solution at about 100°C on the finely divided copper from step B2. About 8 kcal are liberated per mole of H_2 formed, with the use of the gaseous HCl input from step B5. Literature data indicate that, at 80° to 100°C, about 1 mole of CuCl will dissolve in 9 moles of H_2O mixed with 2 moles of HCl. At lower temperatures, the CuCl is considerably less soluble and so it can be separated by cooling the solution, preferably countercurrently, with weak solution so that the overall heat needed for separation is approximately zero; the 8 kcal liberated by step B1 is also available.

Step B2. Two moles of CuCl come from step B1, and 2 moles come from step B3. The disproportionation of CuCl into Cu and $CuCl_2$ is ordinarily rather small ($\Delta G° = 38$ kcal for reaction B2, going from solid to solids). However, the theoretical voltage to split CuCl into Cu and aqueous $CuCl_2$ is only about 0.12 volt. One might consider an electrochemical separation at moderate temperatures with the heat of reaction (33 kcal for solid to solids) supplied partly by the heat of solution of $CuCl_2$ (11 kcal) and partly from I^2R losses and the environment (22 kcal). The theoretical minimum work required for this four-electron transfer step would be about 11 kcal, but composite losses would increase it to 16 kcal or more. To supply 16

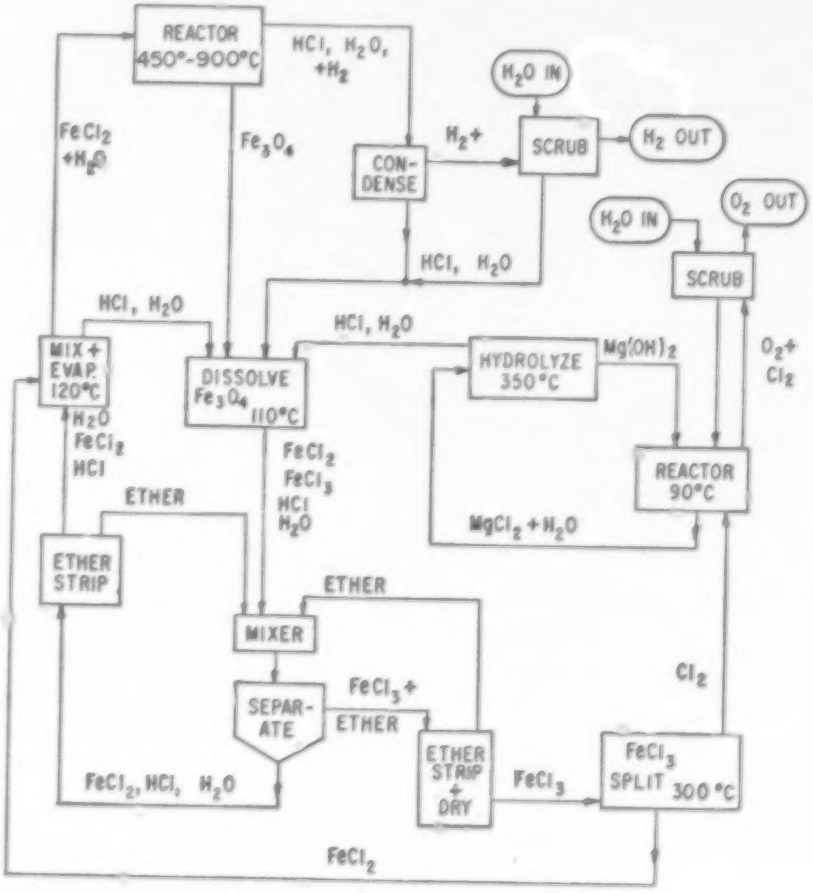

Fig. 2. Simplified flow chart for process A.

Table 2. Thermochemical data for process B.

Step	Reaction temperature (°C)	Energies (kcal) for reactions as written	
		$\Delta H°$	$\Delta G°$
B1	100°	−8	2
B2	30° to 100°	33	38
B3	500° to 600°	32	0
B4	80°	−38	−46
B5	350°	4	8

kcal of electric work requires about 40 kcal of heat from about 500°C. After the electrolytic separation, $CuCl_2$ would be recovered from solution by evaporation and crystallization with waste heat from step B1 plus about 15 kcal near 120°C.

One might also consider disproportionating CuCl by complexing the $CuCl_2$ with a substance χ, which would later be separated from the $CuCl_2$ by processes requiring heat or work. Suitable complexing agents include amines or ion exchange materials. Considerable care is needed to meet the large ΔG requirement economically by using waste heat and environmental sources and sinks, and a total demand of about 55 kcal would be expected.

Step B3. The well-known decomposition of $CuCl_2$ occurs readily at temperatures in the range 450° to 500°C. Nearly all the vapor is Cl_2, and its pressure is about 0.037 atm at 450°C, 0.54 atm at 510°C, and 1.17 atm at 550°C. Pure CuCl has a melting temperature of about 425° to 430°C; its vapor pressure is only about 0.0013 atm at 500°C. Thus, by heating $CuCl_2$ at 600°C, one obtains Cl_2 vapor and molten CuCl which may contain a little $CuCl_2$. Pure $CuCl_2$ melts at approximately 630°C. The decomposition absorbs about 32 kcal per mole of Cl_2.

Steps B4 and B5 are identical to those described above under process A and hence will not be discussed further here. A simplified flow chart for process B is shown in Fig. 3.

The main heat requirements for process B are found in steps B2 (40 kcal at 500°C and 15 kcal at 120°C), B3 (32 kcal at 500° to 600°C), and B5 (26.5 kcal at 350°C, on the assumption that the feed water can be vaporized at about 100°C by the heat from step B4), for a total of 113.5 kcal. Here again, the net heat requirement for a practical process exceeds 68.3 kcal because not all the low-temperature heat released can be used.

If to 113.5 kcal we add ≥ 15 kcal for the inevitable losses and other requirements, the total heat demand is ≥ 128.5 kcal and the thermal yield efficiency ϵ is 57.8/128.5 ≤ 0.45. The thermodynamic process efficiency η^* is 54.6/128.5 ≤ 0.43. The ultimate Carnot efficiency between 550° and 30°C is 0.63, and $\beta \leq 0.67$. Process B is more efficient than process A because it operates at a higher maximum temperature, and, fortuitously, less heat is circulated internally, that is, only about 15 to 20 kcal per mole of H_2 in process B instead of at least 50 kcal in process A.

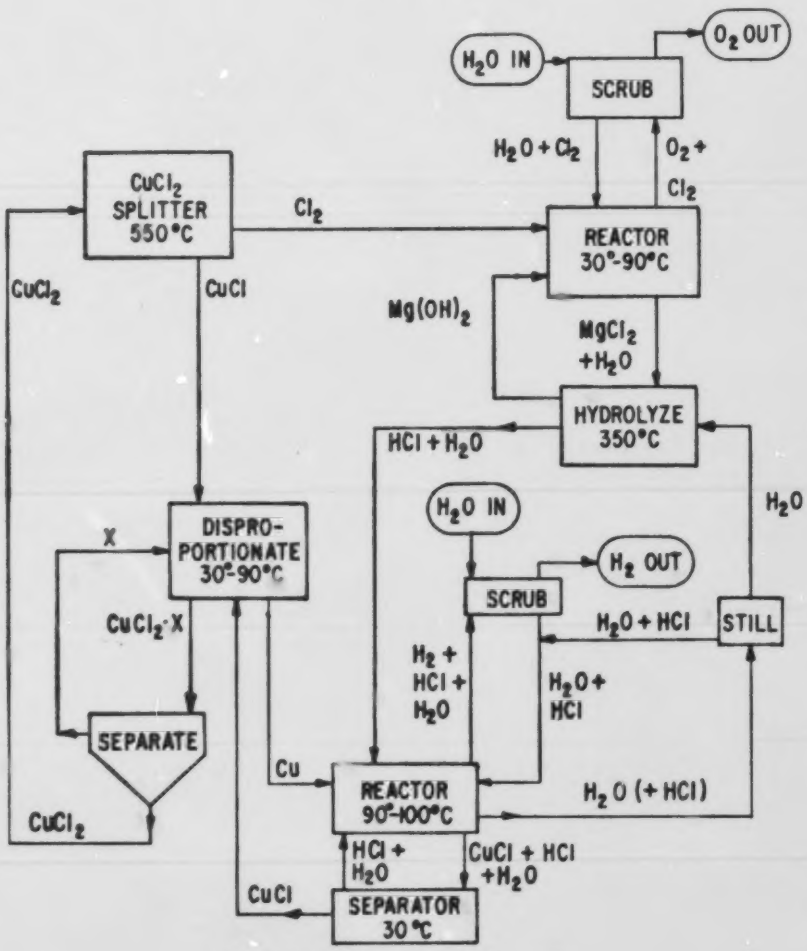

Fig. 3. Simplified flow chart for process B.

Process C

This process appears to be the most eligible of a small family of processes founded mainly on iodine. The following key steps are the basis for the process (see Table 3):

$$3I_2(l) + 6LiOH(aq) \rightarrow 5LiI(aq) + LiIO_3(aq) + 3H_2O(l) \quad (C1)$$

$$LiIO_3(c) + KI(aq) \rightarrow KIO_3(c) + LiI(aq) \quad (C2)$$

$$KIO_3(c) \rightarrow KI(c) + 3/2\,O_2(g) \quad (C3)$$

$$6LiI(l) + 6H_2O(g) \rightarrow 6HI(g) + 6LiOH(l) \quad (C4)$$

$$6HI(aq) + 3Ni(c) \rightarrow 3NiI_2(aq) + 3H_2(g) \quad (C5)$$

$$3NiI_2(c) \rightarrow 3Ni(c) + 3I_2(g) \quad (C6)$$

Step C1. Liquid iodine at about 115°C from step C6 reacts with concentrated aqueous LiOH at about 100°C from step C4. About 44 kcal of heat are evolved per mole of $LiIO_3$ formed. The reaction is already quite rapid at 80°C, but in the process described here we propose to let-it run at 100° to 190°C so as to use the heat to evaporate liquid in other steps.

Iodine does not liberate O_2 directly from water in alkaline solution as does Cl_2 or Br_2. Thus the production of O_2 from I_2 requires several steps.

In preparation for step C2, ethanol is added to the concentrated aqueous solution from step C1; $LiIO_3$ is rather insoluble in ethanol-rich solutions, and nearly all of it precipitates. After this separation, the ethanol is evaporated from the LiI solution and is recycled. The long-term stability of

tincture of iodine indicates that the oxidation of ethanol should be minor as long as the solution is not alkaline; no iodoform was observed to form in short-time laboratory tests of the $LiIO_3$ separation step. Ethanol can be evaporated in double-effect evaporators to make more efficient use of the low-temperature heat evolved in other steps.

Step C2. The $LiIO_3$ is dissolved in the minimum amount of water and mixed with a concentrated aqueous solution of KI, the product of step C3. The solution is then cooled to approximately 0°C, whereupon most of the KIO_3 precipitates. The remaining solution, which contains K^+, Li^+, I^-, and IO_3^-, is partially dewatered and then returned to the ethanol solution where LiI is preferentially taken into solution so that the K^+ remains in the KI-KIO_3 loop.

Step C3. This step is the thermal decomposition of molten KIO_3 to KI and O_2 at 560° to 650°C and 1 atm. If the KIO_3 is free of Li^+, no I_2 is evolved. In practice, some $LiIO_3$ may be carried along; the $LiIO_3$ decomposition yields I_2 and O_2 at slightly lower temperatures, around 500°C, and this I_2 will have to be removed with a small amount of LiOH. A good heat-transfer medium for the decomposition of KIO_3 appears to be pure O_2. About 51 kcal are required per mole of KIO_3 in step C3.

It appears that KIO_3 is a good choice for an O_2 source because of its clean decomposition to O_2 and its relatively slow solubility; $LiIO_3$, and other iodates such as $Ba(IO_3)_2$ which might be easier to form, are unsatisfactory because at temperatures below 850°C they decompose to O_2, I_2, and rather insoluble, intractable paraperiodates such as $Ba_4(IO_6)_2$. Magnesium iodate and some other iodates easily decompose to the metal oxide, I_2, and O_2, but these metal oxides form bases that are either too weak or too insoluble to be of practical use. The sometimes obscure laws of conservation of energy are subtly buried in chemical considerations of this type.

Step C4. Concentrated aqueous LiI reacts with superheated steam at about 475°C or higher and 1 atm to form HI and LiOH. Steam comes along with the HI; in preliminary laboratory tests the condensate contained about 1 percent HI (by weight). Both LiI and LiOH are molten at this temperature and dissolve in each other, thereby lowering the fugacity of the LiI and reducing the HI yield. It is practical to plan on no more than two-thirds of the LiI being hydrolyzed and to feed the steam countercurrently for greater HI yield. The hydrolysis conditions are rather corrosive but carbon seems to survive well as a reactor vessel material. The reaction requires about 19 kcal to produce 6 moles of HI; this heat is supplied by the superheated steam feed. The ΔG° value of 108 kcal/mole is spread over 6 moles of HI gas, and hence the reaction can proceed appreciably as shown.

Table 3. Thermochemical data for process C.

Step	Reaction temperature (°C)	Energies (kcal) for reactions as written	
		ΔH°	ΔG°
C1	100° to 190°	-44	-25
C2	0°	~ 0	~ 0
C3	650°	51	~ 0
C4	450° to 600°	19	108
C5	150°	-58	-20
C6	700°	99	~ 0

The mixture of hot HI and steam leaving the hydrolysis step is condensed to supply low-temperature heat for other steps and is concentrated by partial condensation and distillation. It is then pumped into the reaction vessel for step C5.

Other salts, such as MgI_2, hydrolyze more easily than LiI, but the resulting oxides or hydroxides are too weak as bases to combine with I_2 vigorously and in concentrated solution as in step C1. A stronger base used in step C1, such as $Ca(OH)_2$ or NaOH, is more difficult to hydrolyze, and hence LiOH is a compromise.

Step C5. Hot nickel sponge from step C6 reacts at roughly 10 atm and 150°C with the condensed HI solution to form H_2 and a strong solution of NiI_2. Operating the reaction at a modest pressure eases purification and compression requirements for the product H_2. The H_2 could be conveniently freed of HI if the gas is passed over more nickel sponge. The reaction liberates about 58 kcal for 3 moles of NiI_2 formed. Some of this heat is recovered by condensing water vapor from the H_2 stream; the rest is used to flash water from the NiI_2 solution.

The NiI_2 solution is evaporated by simple heating without appreciable hydrolysis to yield dry NiI_2 for step C6. If one wanted to go to the trouble of drying the HI, one would not need to dry the NiI_2 and then one might operate with fixed beds of Ni/NiI_2. At present, it seems simpler to dry the NiI_2.

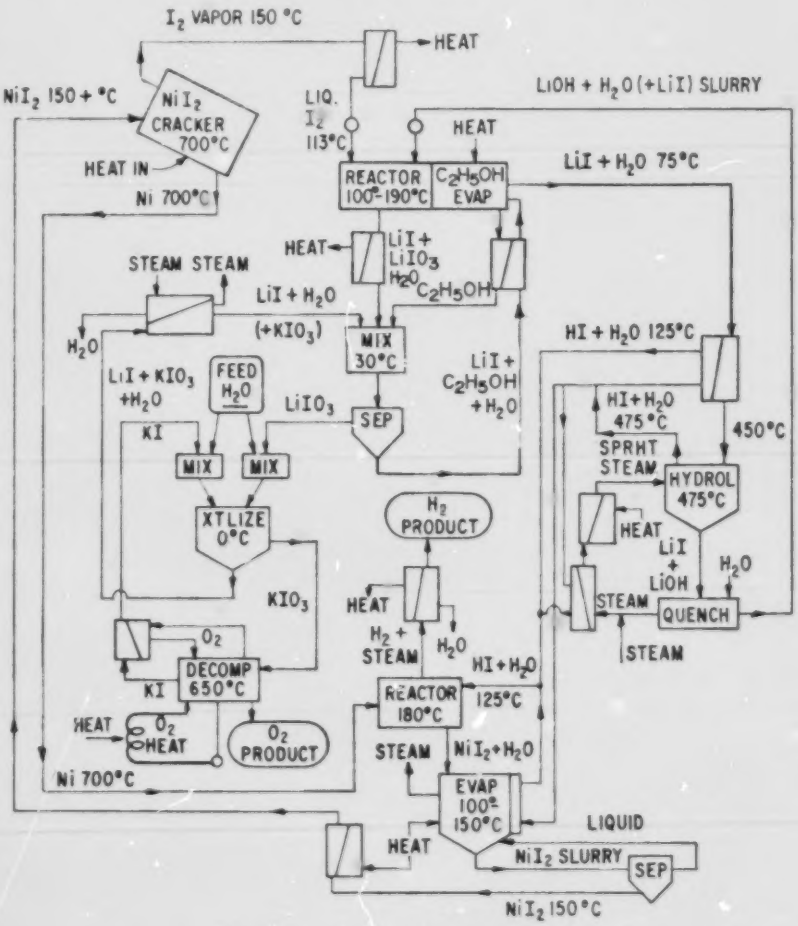

Fig. 4. Simplified flow chart for process C.

Step C6. Dry NiI_2 is thermally cracked at 600° and 750°C to yield nickel sponge and I_2. The incoming salt may be heated directly by the outgoing I_2 and by condensation of any NiI_2 which sublimes without decomposition. Some sort of rotary, inclined kiln may be useful here. The pressure of I_2 is approximately 0.25 atm at 700°C. The reaction is endothermic, about 99 kcal for 3 moles of I_2 formed, and is the largest consumer of high-temperature heat in the process. The hot nickel sponge is used to make H_2 in step C5. Cobalt might be substituted for nickel in steps C5 and C6, although CoI_2 is a little more difficult to decompose. It will be necessary to avoid undesired oxidation of I by excluding O_2 in certain steps of the process.

A simplified flow chart for the various streams is shown in Fig. 4. A rough estimate of heat requirements for the separate steps of process C indicates that about 85 kcal are needed per mole of water decomposed. If to this one adds ≥ 15 kcal for estimated losses, pumps, and the like, one needs ≥ 100 kcal to produce 1 mole of H_2 which yields 57.8 kcal on burning to water vapor, the thermal yield efficiency is thus $57.8/100 \leq 0.58$. The value of n^* is $54.6/100 \leq 0.55$ compared with a limiting Carnot factor of 0.73, and $\beta \leq 0.55/0.73 = 0.75$. More laboratory studies on certain parts of the process will be needed before more precise estimates and design work can be done.

From a general chemical viewpoint, a comparison of processes A and B with process C shows that in going from Cl_2 to I_2, one eases problems of H_2 formation but makes O_2 formation more difficult. Bromine appears to resemble Cl_2 more than I_2 in processes of this type, and there seems to be little incentive to use it.

Other Processes

Mixed thermochemical-electrolytic processes for the generation of hydrogen also offer promise in spite of the fact that they have received little mention in the literature. In such systems electrolytic energy is generally applied to one step of a multistep process, which requires considerably less voltage and losses than direct water electrolysis. The remaining steps of the process then include combinations of the closed-cycle thermochemical processes outlined above. Such mixed-cycle systems may be more readily coupled to utility needs for off-peak energy storage than straight thermochemical systems.

Other approaches to hydrogen production based on biological or photolytic concepts have been suggested (*15*). Photochemical processes based on sunlight offer a genuine, long-term solution to energy supply problems, but the capital investment required could be large so that the energy made available would not necessarily be cheap. Future closed-cycle processes might be involved in converting solar energy to chemical forms, and some of the concepts discussed in this article should be helpful in devising appropriate cycles.

Economic Comparisons and Uses

The cost of hydrogen generated from closed-cycle thermochemical processes can be approximately estimated on the basis of the known costs of high-temperature nuclear heat, the expected process efficiency, and estimates of the capital and operating costs of the thermochemical process equipment itself. The future capital cost of high-temperature gas-cooled reactors in the United States in the 2000- to 4000-megawatt (thermal) size range is estimated to be $240 to $400 per kilowatt (thermal), in current dollars, not including electrical generation and thermochemical process equipment. Based on utility financing, a 90 percent duty cycle, and nuclear fuel cycle costs of $0.40 per 10^6 kilojoules, the total cost of input nuclear heat will be $1.84 to $2.76 per 10^6 kj (that is, $1.74 to $2.60 per 10^6 British thermal units).

The most economical closed-cycle processes will utilize significant displacements from thermodynamic equilibrium so that systems with overall thermal efficiencies of the order of 30 to 40 percent are judged to be more likely practical candidates for eventual commercial use. Accordingly, the heat costs alone for hydrogen generation would range from $5.26 to $7.89 per 10^6 kj at 35 percent efficiency. An approximate analysis of the processes described above yields a minimum additional capital plus operating cost of at least $2 per 10^6 kj. Thus hydrogen from closed-cycle processes is expected to have a minimum potential cost of at least $7.26 per 10^6 kj at the generation plant for processes with 30 to 40 percent efficiency.

The cost of hydrogen produced by electrolysis and by more conventional fossil fuel–based methods has been discussed by several authors (*16–18*). The cost of electrolytic hydrogen in 1985, based on the use of solid polymer electrolysis cells, is projected (*16*) to drop to

$$C_E = 0.312C_O + 0.27$$

where C_E is the hydrogen combustion energy (LHV) expressed in current dollars per 10^6 British thermal units and C_O is the cost of electrical energy in mills per kilowatt-hour. Thus, for off-peak power at 15 mills per kilowatt-hour, C_E would cost nearly $5 per 10^6 kj in 1985. An electrolysis plant would be much cheaper to build and maintain in operation than a closed-cycle thermochemical plant.

The cost of hydrogen produced from open-cycle thermochemical processes using natural gas or petroleum should vary from more than $2 to over $4 per 10^6 kj as the cost of fluid hydrocarbon feedstock varies from $1 to $2 per 10^6 kj.

With petroleum feedstock prices rising, coal is becoming increasingly competitive with all of the above technologies as a source of hydrogen. Preliminary estimates indicate that hydrogen may be made at a cost of $3 to $4 per 10^6 kj, assuming that coal or coal char will be available at approximately $1 per 10^6 kj. Therefore it appears that coal-based processes will tend to become an increasingly important source of hydrogen in the next two decades or more. However, when and where coal or other fossil fuels become more costly or chemical pollution problems are severe, nuclear electrolytic hydrogen production will tend to become economical. Closed-cycle thermochemical processes of the type discussed in this article have only a marginal chance to succeed, mainly because of their relatively large capital costs, together with efficiencies that are not particularly outstanding.

The projected costs of hydrogen indicate that it will not serve as a universal energy medium for the next two decades at least. Rather, hydrogen is expected to play a major role as an increasingly important chemical feedstock for industrial and petrochemical processes and in the conversion of coal into clean synthetic fuels. If it could be made at a sufficiently low cost, liquid hydrogen would be a candidate fuel for aircraft around the year 2000, principally because of its high thrust-to-weight ratio and low pollution effects (*20*).

Over the longer term, when synthetic natural gas and related fossil-based fuels become increasingly expensive or unavailable, hydrogen offers some potential for widespread use in distributed electrical generation systems and as a more general fuel. However, other technologies, such as closed-loop chemical energy transmission (*20, 21*) and advanced electrical transmission systems, will compete strongly with hydrogen as major energy transmission media in the next century.

Conclusions

The basic concepts for thermochemical hydrogen generation processes have been summarized in this article. A useful set of criteria has been described for the screen-

ing and selection of potentially viable, multistep, closed-cycle thermochemical processes for hydrogen generation. Three illustrative closed-cycle processes have been discussed, indicating potential overall thermal efficiencies ranging from approximately 30 to 55 percent. Combined thermochemical-electrochemical schemes may also warrant further consideration. The principal technical problems in the development of such closed-cycle and mixed-cycle processes are expected to involve materials compatibility, reaction kinetics, separation techniques, and heat-exchanger systems.

As natural gas supplies decline and prices rise, new open-cycle thermochemical processes based on water and other fossil fuel feedstocks will be the first important new technology in supplying the growing hydrogen needs of industry for at least the next two decades. Emerging electrolysis technology appears to be increasingly interesting for a variety of uses, although hydrogen will be generally too expensive to use as a fuel.

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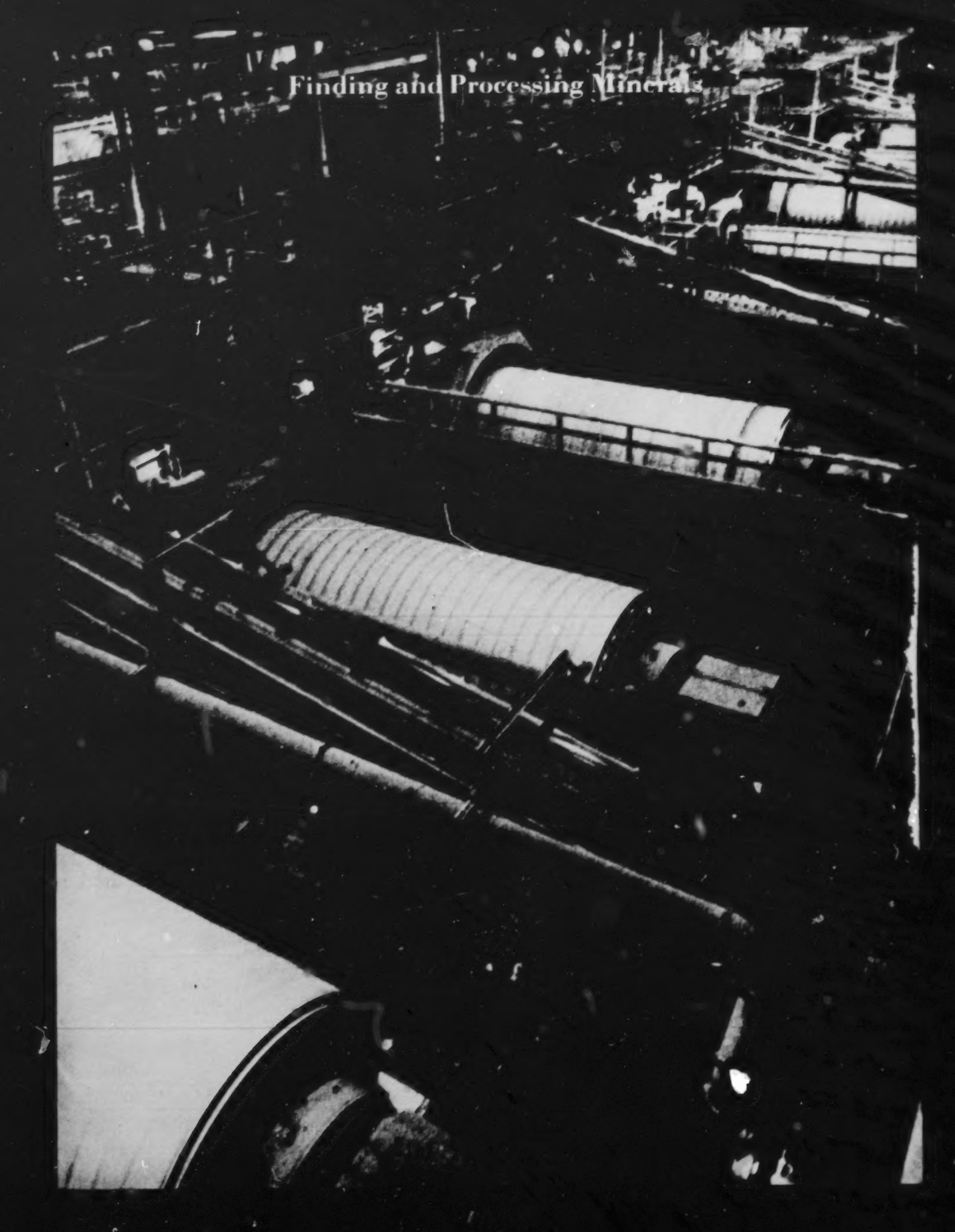
Finding and Processing Minerals

Discovery of Natural Resources

Advances in exploration concepts and techniques offer hope for resource supply.

Philip W. Guild

Ore deposits result from igneous, sedimentary, metamorphic, biologic, and weathering phenomena; their sizes, shapes, and environments are extremely diverse. Finding those of substantial lateral extent, which usually are syngenetic (formed together with their enclosing rocks) or concentrated by supergene (weathering) action at or near the surface, commonly presents few problems, once their environment is recognized. This is not to say that the evaluation of their value—the delineation of reserves—does not require an extensive input of time and money, but rather that their existence can often be established by rather simple technology (or by none at all if they crop out at the surface and hence can be found by chance or by prospecting in the traditional sense).

Deposits of many metals and minerals, and, in particular, of the rarer and more costly ones, are epigenetic (formed later than their enclosing rocks) and hypogene (formed by solutions or gases ascending from deep sources that drop their metals in "favorable," commonly very restricted, locations somewhere near but below the existing land surface). If erosion has subsequently exposed these deposits and if they have not been hidden by younger rocks, deep soils, dense vegetation, or other cover, their discovery merely awaits recognition by an amateur or professional searcher. Few such outcropping deposits remain to be found, however, and exploration is rapidly turning to more and more sophisticated scientific techniques.

These techniques may be categorized as geologic—study of the total observable characteristics of the deposits and their settings; geochemical—measurement of traces of elements in rocks, soils, plants, water, or air that may suggest the proximity of a buried deposit; or geophysical—determination of anomalous values of magnetic, seismic, gravitational, electrical, or electromagnetic (radiation) properties that may be due to ore at depth. Modern prospecting combines many techniques, all of which have as their purpose the designation of target areas for the exceedingly costly physical exploration, usually drilling, that must follow if an actual discovery is to be made.

The hardware employed today ranges from scanning spectrometers carried by satellites to mass spectrometers and electron microscopes; computers are increasingly being used to evaluate the data collected.

Theory

Systematic exploration should be based on a genetic model:

1) How did the deposit form?

2) Where were the conditions favorable?

3) What ancillary features of broader extent might aid in zeroing in on the target?

Exploration based on a false model may be successful, for it is the work, not the theory, that leads to the discovery of ore, but, as deposits become more difficult to detect, it is inevitable that the discovery record should correlate positively with the correctness of the model.

On the global scale, plate tectonic theory has brought a degree of order into economic geology by providing a conceptual framework into which deposits of various types can be fitted and their known distribution explained. For example, most, if not all the porphyry deposits occur near converging plate margins on the overriding, continental or island-arc side (Fig. 1). Copper and other metals are known to be present at mid-ocean rifts where new lithosphere is forming; this observation suggests that the initial low concentration might have taken place there, subsequently to be intensified when the ocean lithosphere was subducted, fused, and introduced as magma to produce the extrusive and intrusive rocks with which the deposits are associated. Hence areas known to be situated over active subduction zones, marked by seismic activity (the Benioff planes), are favorable for prospecting, and successful campaigns have been conducted in several areas of the world since this principle was recognized. Older convergent margins can be deduced from the characteristic magmatic products and structural features; these also are useful general guides to the selection of areas for exploration.

Other deposit types, notably of lead, zinc, barite, and fluorite (the so-called Mississippi Valley and related ores), are formed in continental interiors, as are deposits of niobium, vanadium, titanium, the rare earths, and phosphorus-rich iron ores of igneous affiliation. At least some of these deposits seem to be associated with deep, persistent crustal fractures (lineaments) that may be related to the breakup or aborted past fragmentation of the continents. An intermediate group of deposits seems to have features, and plate positions, that combine aspects of subduction- and lineament-related ores. Some recent investigators (*1*) have drawn attention to apparent segmentation of the subducting oceanic lithosphere, which might be inherited from preexisting fractures, and have attempted to correlate ore distribution to the intersections of lineaments and Benioff zones.

Plate tectonics is thus stimulating, even revitalizing, the theory of ore deposition and promises to be increasingly useful as the details are worked out. However, except as a first-order guide for selecting prospecting areas, its role in the discovery of ore bodies is now, and probably will always be, of little practical importance. This conclusion derives from the matter of scale; even the largest epigenetic deposit is minute in relation to an orogenic belt, and understanding why a known deposit is located in a given region of the world does little to pinpoint a buried one. Far more exhaustive studies are required.

Application

Obviously, there is no universally accepted "best" method in exploration; the simplest, quickest, and least expensive method that finds ore is naturally the one to use. As mineral exploration is a highly competitive game in capitalist countries, details of current practices tend to be proprietary, especially as they reflect the exact "mix" of technologies employed. Modern ore search can be likened to a scientific ex-

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← *Courtesy Tilden Plant, Cleveland Iron Ore Company*

periment in which one or more models (hypotheses) are compared with the observed facts to evaluate clues that will progressively restrict the volume of rock to be tested with the drill. New methods, combinations of methods, and, in particular, new tools are needed as the deposits remaining to be found become more elusive.

In practice, the explorationist begins by assembling and evaluating all the information available to him about the area under consideration. If this is small, as, for example, within or near a mining district, there may be a wealth of maps, drill hole data, and reports of previous investigators that will require only a fresh point of view to be "read" correctly. Thus Lowell (*2*) found the Kalamazoo porphyry copper deposit in Arizona with the first drill hole at a depth of 2500 feet (760 m) after reinterpreting evidence gathered from earlier studies of the nearby San Manuel ore body. The latter, which cropped out, had been tilted and broken into two approximately equal pieces; most investigators had believed the missing half to have been raised and eroded, or moved laterally an unknown distance, but Lowell correctly diagnosed both fault-plane geometry and the alteration pattern to find the deposit 8000 feet from its original position.

Although geologic maps are now available for most of the earth, those of many regions are at very small scales and give at best only a gross approximation of the actual situation; in any case maps cannot in themselves reveal concealed ore bodies but only suggest favorable places to look.

Remote Sensing

The selection of target areas for detailed ground investigation can be aided greatly by remote sensing from aircraft and satellite. Advantages include speed, the ability to cover areas having poor or no transportation facilities, the synoptic view of larger areas than can be seen from the ground, and the employment of sensors that are not practicable for field use. Most remote-sensing methods are "passive": they record reflected solar radiation (from ultraviolet to infrared) on film or by scanning devices, perturbations in the earth's magnetic field, or gamma-ray emission from radioactive elements. A few are "active": side-looking radar records the reflectance of microwaves ($\sim 10^9$ hertz) emitted from an airplane; the airborne electromagnetic method transmits very-low-frequency (100 to 4000 hertz) radiation from the plane to the ground and detects phase changes or decay times of currents induced in the earth (perhaps by ore deposits). Some may be considered as intermediate: natural fluctuations in electromagnetic fields generated by lightning discharges (100 to 500 hertz) or very-low-frequency (3 to 30 khz) radio transmitters can be measured in low-flying aircraft (*3*).

The Landsat [formerly Earth Resources Technology Satellite (ERTS)] satellites circle the earth in near-polar, sun-synchronous orbits 14 times per day at altitudes of about 910 kilometers. Multispectral scanners (MSS) record the energy reflected in four bands, two in the visible spectrum, 0.5 to 0.6 and 0.6 to 0.7 micrometer, and two in the near-infrared, 0.7 to 0.8 and 0.8 to 1.1 micrometers, across a strip 185 kilometers wide and transmit the data in digital form to receiving stations. Coverage is completed every 18 days. The digital data are converted to black-and-white images which resemble photographs and may be studied directly or converted in various ways and combinations to colored images that can greatly enhance contrasts and emphasize desired features. The satellites cross the equator on their southward passage at about 9:30 a.m. local time; hence, the rather low sun angle and resultant shadows reveal topographic features clearly. Seasonal variations (for example, light snow cover) also are very helpful. A resolution of about 80 meters is adequate for many geologic purposes, and the area that can be observed on a single scene (some 35,000 square kilometers) facilitates detection of linear and curvilinear features that were previously unknown even in well-mapped regions. Because many ore deposits are known or suspected to be localized by lineaments or by intersections of two or more lineaments, or to be near the periphery of circular features that may be of igneous origin, examination of Landsat imagery is being used increasingly as a first step in exploration (*4*). The selection last year of a site for drilling that coincided with the location of a medium-sized porphyry copper deposit in Arizona has been credited to the study of satellite data.

Further computer processing of the MSS data, already on tape, can reveal subtle differences not detectable by visual observation of the standard images. As reflectance is measured for each band of an area (50 by 80 meters) of the surface and recorded as a digital number, ratioing of the numbers for different bands will produce new sets of values. In this way albedo and topographic effects (brighter or darker slopes) are reduced, and response due to absorption bands (chiefly of ferrous and ferric iron, subordinately of other metals and of hydrous minerals) is enhanced. Because much of the critical information is contained in only part of the range of digital numbers, both the original and ratioed values can be "stretched" to increase the contrast still more. Black-and-white images produced from the ratioed, stretched, or ratioed and stretched data are then converted into color composites. Many rock types and, of particular interest for exploration, areas of alteration probably due to mineralizing processes have been distinguished by Rowan and his co-workers (*5*) in the Goldfield mining district, Nevada.

A digital-processing program that compared the spectral "signatures" in the four MSS bands obtained from an unexploited porphyry copper deposit in Pakistan enabled Schmidt (*6*) to make a computer-plotted "map" of the surrounding unexplored region that showed other areas giving similar responses. Of 19 sites subsequently visited, five were found to have sulfide-bearing, hydrothermally altered rock and seem to be parts of porphyry copper systems.

The direct application of satellites to mineral exploration has been most successful in arid, poorly known regions. Future improvements in methodology, and especially in the use of sensors designed specifically for geologic purposes, should greatly improve the already impressive record. Most future discoveries will undoubtedly require, however, the conjunction of several tools, deployed both by aircraft and on the ground.

Low-flying (100 to 300 meters above terrain) aircraft carrying or towing instruments capable of measuring changes as small as 1 part per million in the earth's magnetic field easily detect buried magnetite (Fe_3O_4) deposits, and, because many types of rock contain small but more or less characteristic amounts of accessory magnetite (or other, less magnetic minerals), maps made from the data are immensely useful for refining geologic knowledge, especially in poorly exposed areas. A few nonferrous deposits contain sufficient magnetite to be detected directly, but the principal value of aeromagnetic maps in exploration for most ores is in narrowing the search for favorable areas (which may be studied in greater detail by ground magnetic surveys).

Airborne gamma-ray spectrometers, which can be carried in the same aircraft with magnetometers, can distinguish radiation emanating from elements of the ^{238}U and ^{232}Th series and from ^{40}K, each of geologic significance. Only the uppermost surface materials contribute to this radiation because even very thin cover will effectively stop it; nevertheless, the method can detect exposed uranium deposits directly or suggest areas whose buried deposits are

"leaking" daughter products. Monazite, a thorium-bearing mineral, frequently accompanies "black sand" deposits of titanium minerals; such a deposit was found recently in Georgia on the site of an anomaly discovered during the course of an aeroradiometric survey by the U.S. Geological Survey (7). Potassic alteration accompanies some epigenetic mineralization; theoretically, a ^{40}K anomaly could be a guide to exploration.

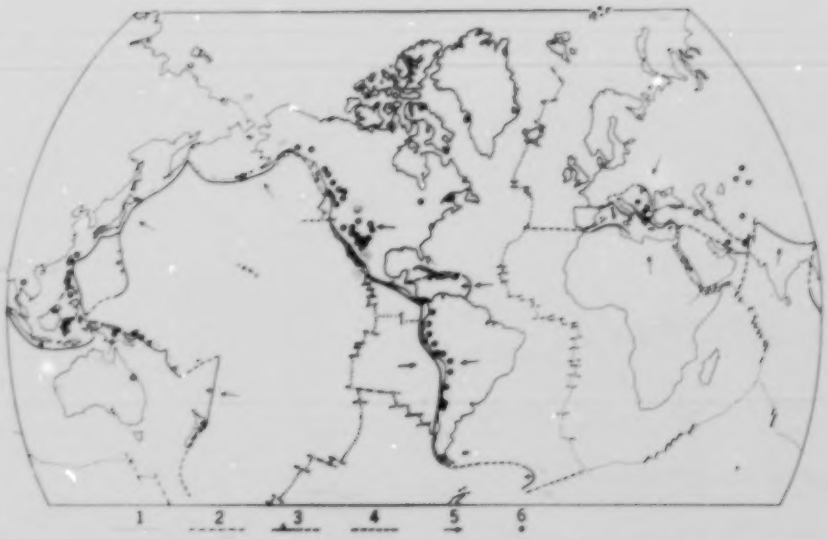

Fig. 1. Distribution of porphyry copper and molybdenum deposits in relation to the major lithospheric plates: *1*, accreting plate margin; *2*, transform plate margin; *3*, consuming plate margin showing the dip direction of the downgoing plate; *4*, margin of uncertain nature or location, or both; *5*, relative plate motion; and *6*, porphyry deposit. [Modified from (*18*), figure 4; courtesy of Springer-Verlag, New York]

Field and Laboratory Studies

As helpful as remote-sensing methods are, detailed ground studies are indispensable to all but the most fortuitous discoveries. These studies embrace too wide a range to treat even briefly here, but the chemical and physical nature, spatial distribution, and mutual relations of the rocks that hopefully contain ore must be worked out to provide the best guidance possible for the physical exploration to follow. Geologic mapping is fundamental; identification of rocks by inspection, chemical analysis, and study of thin sections of rocks in polarized light under the petrographic microscope is routine. Wet chemistry, atomic absorption, emission spectrometry, x-ray fluorescence, neutron-activation analysis, and electron diffraction are used as appropriate to determine the chemical composition of rocks and minerals. X-ray diffraction and both transmission and scanning electron microscopes are increasingly being employed for the identification of mineral phases.

Age determinations are particularly critical to the interpretation of the geology of any area. Paleontology, where applicable, can unravel complex structural situations and also provide clues to the depositional environment (shelf, shallow-water or deep-water marine, lacustrine, or whatever) that may assist in exploration for stratabound deposits. Radioactive age determinations, principally by the uranium-lead, potassium-argon, or rubidium-strontium methods, can often give good results on intrusive and volcanic rocks.

The information gained from field and laboratory is ordinarily plotted on maps; prediction of the third dimension is made on cross sections constructed from all available data. Gravity, seismic, magnetic, and electrical geophysical surveys may be especially useful at this stage to assist in choosing between alternative interpretations suggested by the geologic data.

The explorationist has another tool, geochemical prospecting, that involves systematically collecting hundreds or thousands of samples of rocks, soils, stream sediments, plants, water, or air, analyzing them for one or many elements in the field or laboratory, and examining the results by inspection or, more frequently, by computer-aided statistical methods for anomalous patterns that can guide further work (*8*). Anomalies may be primary, due to the same processes responsible for the ore deposit but extending greater or lesser distances beyond the deposit itself, or secondary, formed more or less near the present surface and completely unrelated to the original mineralizing processes. Both types can give clues to the presence of buried ore.

Primary halos or aureoles may consist of lower grade envelopes of one or more of the metals sought, or they may involve simple or complex additions or subtractions of any of many elements—silicon, potassium, magnesium, iron, sulfur, or others. Oxidation of iron sulfide (pyrite) produces the familiar red staining that led to the discovery of many near-surface deposits in the past; less obvious alteration effects require much more sophisticated geological, mineralogical, and particularly geochemical studies before interpretations can be made.

Studies of the dispersion halos around known districts are indispensable to an understanding of the behavior of the elements during the mineralization process. Analysis of about 2000 samples for each of 30 elements from the Robinson mining district near Ely, Nevada, and subsequent computer-processing of the 60 000 numbers obtained revealed a more or less concentric pattern outward from copper (the chief ore metal) and iron to lead, zinc, and silver, then the more volatile elements, namely, cobalt, mercury, gallium, tin, indium, and thallium. Robinson and his coworkers (9, p. 14) concluded that thallium and, to a lesser extent, indium have traveled farthest and may be sensitive indicators of concealed ore deposits.

Geologic events subsequent to mineralization can remobilize and redistribute volatile elements, complicating the patterns but also providing additional evidence for the unraveling of complex structural situations. Thus, halos of sulfur, tellurium, and cadmium are concentric around small intrusive stocks in the Coeur d'Alene district of Idaho that are known to be post-mineralization on the basis of lead isotope and other evidence (9, p. 14).

Most geochemical prospecting focuses on the search for secondary halos. These can be in situ, over a still buried body and due to groundwater percolating through or volatiles given off by the ore, or they may extend considerable distances downslope and be detectable in much of the drainage area. The latter situation may be due to partial erosion and subsequent covering of a deposit, to complete erosion of one or more deposits in the recent geologic past, or to some other combination of events. Placer deposits of gold, platinum, diamonds, and other heavy, chemically inert metals and minerals may be considered as classic examples of secondary halos, except that these have frequently been upgraded to economic status from original deposits too small or low grade to be min-

able, in contrast to most of those sought today, which are orders of magnitude lower.

Remote-sensing extends even to geochemical prospecting, for, although most sampling is done by field methods, airborne instruments capable of detecting mercury, sulfur compounds, halogens, and other volatiles are being developed and tested. Abnormal concentrations of metals in soils cause stress in certain plant species that may be detectable by spectral analysis. Research on these and many other fronts is going on in most of the world.

Fluid inclusions trap samples of mineralizing solutions during crystal growth and are potentially useful as prospecting guides (*10*). Although inclusions are tiny, averaging perhaps 10 micrometers and rarely as large as 1 millimeter in diameter, a surprising amount of information on composition, temperature and depth of crystallization, and source of the solutions can be obtained on heating and cooling microscope stages, by laser-excited Raman spectroscopy of solid, liquid, and gaseous phases (*11*), and by extracting and analyzing the minute quantities of liquid and gas contained in them. Liquids in quartz deposited during the mineralization phase that produced porphyry copper-molybdenum deposits have been shown to be more saline than liquids in other quartz; as quartz resists chemical breakdown during the weathering phase, a study of its fluid inclusions can suggest the existence of deposits even in soils or transported alluvium where metal ions might be completely leached and dispersed (*12*).

In spite of all the help that remote-sensing, geophysics, and geochemistry can provide, sheer geologic reasoning, persistence, and a degree of luck have been responsible for some of the spectacular discoveries of blind ore bodies.

An outstanding example is the Henderson molybdenum deposit in the Front Range 64 kilometers west of Denver, where Wallace headed a team that found ore worth several billion dollars at a depth of more than 3000 feet (*13*). The key was the deciphering of complex, multiphase intrusions and mineralizing events at the similar Climax deposit (*14*) 48 kilometers away and the application of criteria learned there over many years of study to exploration for a deposit suspected of underlying a small outcropping ore body on Red Mountain. The large, deep deposit was not a faulted segment but an entirely new one; the detective work that led to success would more than do credit to any fictional sleuth.

The application of virtually all the methods discussed heretofore to the appraisal of the mineral-resource potential of a large, relatively unknown region is exemplified by a series of maps and short texts on the Nabesna quadrangle, an area of south-central Alaska extending about 150 kilometers west from the Canadian boundary between latitudes 62° and 63°N and covering some 17,600 square kilometers (*15*). The results of sporadic geological reconnaissance studies dating back to 1898 were incorporated into systematic mapping of much of the area at 1 : 63,360 (1 mile to the inch) during the period from 1967 to 1974; this work was reduced to 1 : 250,000 (~ 4 miles to the inch) and completed with more reconnaissance work to produce the basic geologic map (MF-655 A) for the appraisal. Analysis of about 1350 stream-sediment samples collected during the mapping provided data for geochemical maps showing the distribution of copper, lead, gold, chromium, and cobalt (MF-655 B–F) on a simplified geologic base and for computer-plotted perspective diagrams that emphasize the anomalous areas. Perspective diagrams for silver, lanthanum, molybdenum, nickel, vanadium, yttrium, and zinc showing relationships of the anomalous areas to principal geologic features are on yet another sheet (MF-655 G). An aeromagnetic contour map and interpretation of the anomalies in geologic terms form another pair of maps (MF-655 H, sheets 1 and 2), and a gravity map with interpretation of Bouger anomalies yet another (MF-655 I). The ERTS-1 satellite imagery, computer-processed by ratioing, stretching, and both simulated true- and false-color compositing, was examined for linear and circular features and for color anomalies. The results are shown on both a map and a halftone reproduction of band 4 (0.5 to 0.6 micrometer) imagery with interpretation of the very numerous features detected in terms of their possible relationship to mineral occurrence.

The mineral-resource potential of the Nabesna quadrangle (MF-655 K) was estimated on the basis of known mineral occurrences (and production records, if any), geology, geochemistry, the geophysical and ERTS-derived information, and by assessment of the statistical probability based on the resources of geologically similar, better known regions. Some 25 areas were evaluated and ranked on the basis of criteria that included (i) known deposits, (ii) favorable rock types, (iii) observed surface alteration, (iv) color anomalies in ERTS imagery, (v) alteration suggested by aeromagnetic data, (vi) proximity to intrusives of ages (from isotopic dating) or compositions thought to be favorable, and (vii) the presence of faults or other structures suggested by ERTS, aeromagnetics, or outcrop pattern. Some exploration had already been done by private companies; portions of their results were made available for the government study, which should in turn be very useful for future exploration by industry. A final map (MF-655 L) shows the status of the land (national park or forest, state, native village, or whatever).

The Nabesna quadrangle study is only the initial unit of a program to be extended eventually to the entire state; it can be taken as one example of the nature and range of scientific studies required to provide the groundwork for detailed exploration.

Earth-science research does not have to be directed specifically toward mineral-resource exploration, however, as from time to time important discoveries are made during the course of investigations having entirely different objectives. Undoubtedly the best example in modern times was recognition of the metalliferous brines and muds in the Red Sea deeps (*16*), found during oceanographic work. An older similar discovery was that of the manganese nodules of the deep ocean floor found by the Challenger Expedition.

Summary and Conclusions

Mankind will continue to need ores of more or less the types and grades used today to supply its needs for new mineral raw materials, at least until fusion or some other relatively cheap, inexhaustible energy source is developed. Most deposits being mined today were exposed at the surface or found by relatively simple geophysical or other prospecting techniques, but many of these will be depleted in the foreseeable future. The discovery of deeper or less obvious deposits to replace them will require the conjunction of science and technology to deduce the laws that governed the concentration of elements into ores and to detect and evaluate the evidence of their whereabouts.

Great theoretical advances are being made to explain the origins of ore deposits and understand the general reasons for their localization. These advances have unquestionable value for exploration. Even a large deposit is, however, very small, and, with few exceptions, it was formed under conditions that have long since ceased to exist. The explorationist must suppress a great deal of "noise" to read and interpret correctly the "signals" that can define targets and guide the drilling required to find it.

Is enough being done to ensure the long-term availability of mineral raw materials? The answer is probably no, in view of the expanding consumption and the difficulty of finding new deposits, but ingenuity, per-

sistence, and continued development of new methods and tools to add to those already at hand should put off the day of "doing without" for many years.

The possibility of resource exhaustion, especially in view of the long and increasing lead time needed to carry out basic field and laboratory studies in geology, geophysics, and geochemistry and to synthesize and analyze the information gained from them counsels against any letting down of our guard, however (*17*). Research and exploration by government, academia, and industry must be supported and encouraged; we cannot wait until an eleventh hour to mount a "crash program."

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A Conceptual Revolution Linking Minerals and Plate Tectonics

Allen L. Hammond

Drastically higher prices for oil and declining U.S. production have drawn attention to supplies of other key industrial materials, especially minerals. Although immediate shortages do not appear likely, some authorities have expressed concern about the extent of U.S. dependence on other countries for supplies of chromium, manganese, and other metals. Moreover, depletion of high grade ores and environmental regulations affecting mining and ore processing are expected to increasingly constrain the availability of minerals.

Fortunately, renewed interest in minerals comes at a time of excitement and sweeping new ideas in the study of mineral deposits. The new ideas reflect the impact on economic geology of plate tectonic models for the evolution of the earth's crust. Many ore deposits, for example, are now known to occur at present or past boundaries of the huge crustal plates whose movements have shaped and reshaped the earth's surface. What ores are formed and where they are placed in the crust, it is proposed, depend principally on the tectonic history of a particular region; several models of the processes involved have been put forward. Similarly, it is proposed that the interaction of seawater with cooling volcanic rock is the principal means by which many metals are extracted and concentrated into economically valuable ore bodies; thus hydrothermal rather than magmatic processes are the key to understanding the geochemistry of ore deposits. These proposals and others have stimulated a host of more detailed investigations. Many geologists believe that these developments portend a fundamentally new understanding of the origin of minerals and are laying the scientific foundation for a new era in mineral exploration.

Not all mineral deposits fit the new conceptual framework, but many major classes of metal ores are explicable in its terms. The evolving theoretical models provide detailed if still controversial explanations for the chemistry, mineralogy, and stratigraphic location of these deposits and thus a host of clues with which to look for still undiscovered mineral deposits, some of which are finding tentative use in the mineral industry. They also have implications for the evolution of the earth's crust; similarities between recent and more ancient ore bodies are seen by some researchers as evidence that tectonic processes not unlike those of the present geologic era occurred throughout most of geologic history.

Many metallic ores are now widely recognized to be of volcanic origin in the sense that they occur in volcanic or igneous rocks and were formed at the same time as those rocks. According to plate tectonic theory, volcanism occurs in several circumstances: at diverging plate boundaries (mid-ocean ridges or other centers of seafloor spreading), where mantle material rises to form new oceanic crust; at converging boundaries, where crustal plates descend into the mantle in a process known as subduction, leading to volcanism that forms chains of mountains or oceanic island arcs; and, less frequently, over hot spots caused by ascending plumes of mantle material (Fig. 1). Each of these processes, except possibly the last, is now thought to give rise to a characteristic type or types of ore deposits.

One of the clearest examples—and one which has had major impact on the thinking of economic geologists—is found on the Mediterranean island of Cyprus, long a rich source of copper. The copper sulfide ore occurs in the Troodos area of Cyprus in a distinctive sequence of rocks: on top, sediments of a type formed on the ocean floor; beneath the sediments, pillow lavas formed when molten volcanic material erupts into seawater; farther down, vertical sheets or dikes of basaltic rocks formed as rifts or cracks in the ocean floor are filled from below with volcanic material; and on the bottom, ultramafic rocks (rich in magnesium and iron) that are believed to be characteristic of the earth's mantle. This progression of rock types is known to geologists as an ophiolitic sequence. About the time that economic geologists recognized copper sulfide deposits as an integral part of these rocks on Cyprus, other geologists recognized the ophiolitic sequence as exactly that which should be formed at a mid-ocean ridge. Thus the Troodos area is

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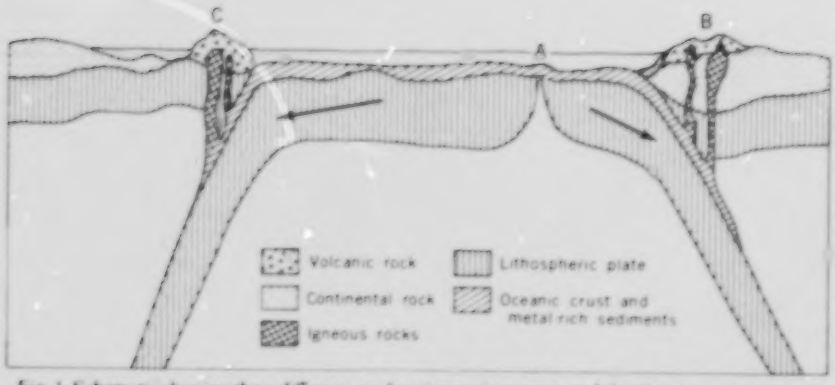

Fig. 1. Schematic showing three different ore-forming environments and the plate-tectonic phenomena postulated to give rise to them: (A) a mid-ocean ridge or rise, (B) a subduction zone underlying a continental margin, and (C) a subduction zone underlying an island arc. Arrows indicate direction of motion of the plates.

now thought to be a largely unaltered piece of oceanic crust thrust up when Cyprus was formed, and the mineral deposits it contains are thought to be characteristic of those formed at mid-ocean ridges.

The minerals include sulfides of copper, iron, and sometimes zinc embedded in the pillow lavas, small masses or "pods" of chromium ore near the top of the ultramafic layer, and asbestos deposits, also in the ultramafic rock. Although not present on Cyprus, lateritic nickel deposits are sometimes found in sections of oceanic crust where ultramafic rock (which is rich in nickel) has been exposed and weathered. Mineral deposits of the Troodos type are found in many parts of the world, including the northeastern United States and eastern Canada. They range in age from the geologically young deposits of Cyprus to older deposits that originated as many as 600 million years ago.

A second major type of mineral deposits—large bodies of low grade ores known as porphyry coppers—are commonly associated with converging plate boundaries. A prime example is the extensive copper deposits in the Andes, where the eastward-moving oceanic crust of the Pacific plunges under the lighter material of the westward-moving South American continent. Partial melting of the downward-moving oceanic plate is believed to generate magmas that rise through the overlying continental rocks, sometimes reaching the surface to form volcanoes. The upper portions of the pipelike stalks or cores of these magmatic intrusions into the surrounding continental rock often contain copper and molybdenum, and sometimes gold and silver as well. Several investigators have studied this process, including Richard Sillitoe, formerly of the Instituto de Investigaciones Geológicas, Santiago, Chile, and now at Imperial College, London; P. W. Guild of the U.S. Geological Survey, Reston, Virginia; Andrew Mitchell of Oxford University; and M. S. Garson of the Institute of Geological Sciences, London. They propose that formation of porphyry ore deposits is a normal facet of the processes that generate the igneous rocks in which they occur. Sillitoe, for example, suggests that the metals of the porphyry ores were initially incorporated in oceanic crust at the mid-ocean ridge, transported horizontally by the movement of the plate, and then released as the downward-moving plate is heated.

Porphyry copper deposits account for more than half the world's supply of that metal. In addition to the porphyry deposits in the Andes, there are deposits in western North America, in parts of the Alpine belt of Europe, and in Iran and Pakistan. Although normally associated with continental rocks, porphyry deposits are also found in some of the larger volcanic islands of the southwest Pacific. Most of these deposits are geologically youthful, less than 200 million years in age. Highly eroded remains of older deposits have been found, however, in northeast North America. Even in the richest porphyry ores, however, copper rarely exceeds 1 percent, and 0.5 percent is more common, so mining consequently involves extracting and processing large tonnages of ore. The association of porphyry deposits with the subduction of oceanic crust into the mantle and the concomitant magmatic activity is so strong that it has been the basis for exploration efforts. A major exception, however, may be the porphyry deposits in Arizona, which according to J. David Lowell of the University of Arizona do not show evidence of a subduction zone. In recent years new porphyry deposits have been found in Okinawa, Panama, and British Columbia.

Deposits of a third distinctive type, known as massive sulfides because they often occur as large, nearly pure lenses of high grade ore, are found in modern island arcs and some geologically older island arc materials that are now incorporated in continental margins. These deposits, like the porphyry coppers, are associated with the convergence of two crustal plates. They are typically polymetallic, containing copper, zinc, lead, gold, and silver.

The prototype deposits for investigators unraveling the origin of these massive sulfides have been those in northeast Japan. This black "Kuroko" ore is thought to have been formed by submarine volcanic processes and deposited in shallow, near-shore environments late in the evolutionary history of a volcanic island chain. The volcanic rocks associated with these deposits are correspondingly highly evolved and often include fragments from explosive eruptions. Marine sediments are also often found with such deposits.

A second variety of massive sulfide ores—those of the Besshi type—are also found in island arcs. Besshi copper and iron sulfide ores (named after a deposit on Shikoku Island, Japan) are, like the Kuroko ores, commonly thought to be submarine volcanic emissions, but deposited on the underwater slopes of volcanoes early in their evolution. Still other classes or subclasses of island arc mineral deposits, corresponding to additional stages in the evolution of these fragments of land, can be distinguished. In fact, a model of the process proposed by Mitchell and J. D. Bell, also of Oxford University, describes seven such stages. They give the timing and accompanying rock types for the formation of Besshi and Kuroko massive sulfides, porphyry coppers, and exogenous mineral deposits (those not formed at the same time as the surrounding volcanic rocks) found in island arcs.

As the plates move, island arcs may be swept into and incorporated in continental masses. And because continents collide, it is not surprising that island arc fragments have been identified in what are now continental interiors. This is significant because a second and major source of massive sulfide and precious metal deposits is the so-called greenstone belts found in ancient Precambrian areas of continents. These belts have historically been the source of much of the world's mineral wealth, with rich deposits ranging from iron ores, important gold deposits, copper and zinc to lead and silver ores.

The Precambrian mineral ores, like younger massive sulfide deposits, are believed to result from submarine volcanic processes. The volcanic rocks associated with these ancient mineral deposits also show chemical and mineralogical similarities to those of island arcs. Hence some geologists believe that greenstone

belts represent ancient island arcs. Since some of the Canadian belts date back at least 3 billion years, this would imply the existence of tectonic mechanisms similar to those that create modern island arcs throughout much of the earth's history, a conclusion that is still controversial. If crustal plates did exist in the Precambrian era, 600 million years ago and earlier, they were apparently much smaller but possibly more numerous; the greenstone belts tend to be hundreds of kilometers in length, not thousands of kilometers like modern island arcs. In any case, the similarities and differences between old and young ore types may be important for exploration—rocks, presumably ancient, that underlie the upper portions of the continents are largely unexplored.

A final class of mineral deposits, whose tectonic derivation is much more speculative, are those ores thought to be formed within a crustal plate, rather than at its boundary. Here the proposed mechanism is penetration of mantle material up through the crust to form a hot spot, possibly as a result of the mantle plumes which have been hypothesized as a driving force for the motion of the crustal plates. Hot spots, investigators are suggesting, may have heated the crustal rock, mobilizing metals from sedimentary or crustal materials and concentrating and depositing them nearer the surface. Guild, for example, proposes that the rich lead-zinc ores of the Mississippi Valley may have originated in this fashion. Similar proposals have been made for lead-zinc deposits in northwest Africa. In some instances, Guild believes, the minerals themselves have come from the mantle, propelled up through the crust by the heat of the plume. Diamonds, niobium, and some rare-earth deposits, for example, are associated with the explosive eruption of mantle materials to the surface and may be attributable to a plume mechanism. Heat from the mantle, perhaps rising near subduction zones, may also provide the energy to mobilize metals present in lower crustal rocks and concentrate them into ore deposits in some circumstances. This mechanism has been proposed to explain the eastward shift from dominantly copper to dominantly lead-silver ores in western North America, and the repeated emplacement of tin ores in only a few areas of the earth.

Newfoundland Mineral Deposits

A striking illustration of the new models of mineral formation is their application to Newfoundland by David F. Strong and his colleagues of the Memorial University, St. John's. Before the opening of the Atlantic Ocean and the separation of North America from Eurasia about 200 million years ago, according to plate tectonic theory, the Appalachian mountains of eastern North America and the Caledonian range in Britain and Norway formed a continuous mountain belt. Although the details of how this ancient mountain range was formed are still a matter of debate, the basic process is thought to have been the opening and eventually the closing of a predecessor or "proto-Atlantic" Ocean between about 600 and 450 million years ago. Since Newfoundland sits astride the Appalachian-Caledonian range, it is in many ways an ideal laboratory for exploring how a tectonic cycle that involved the formation and then destruction of large amounts of oceanic crust affected the formation of metallic ores.

The Newfoundland investigators find that most mineral deposits on the island can be classified in terms of specific plate tectonic origins. They include Troodos-type ores in ophiolitic rock assemblages, Kuroko-type ores in volcanic rocks typical of island arcs, porphyry copper deposits in igneous rocks, and Mississippi Valley type lead-zinc ores.

The geology of Newfoundland is complex and the ore deposits are distributed in both age and location. The eastern and western parts of the island are composed primarily of ancient Precambrian rock (older than 600 million years), while the center part of the island is of more recent origin, formed during the proto-Atlantic event and sandwiched in between the older crust as the ocean basin disappeared. Along the western margins of the island are limestones and dolomites, some of which contain Mississippi Valley type lead-zinc ores. These rocks were apparently deposited in shallow waters during the early part of the proto-Atlantic era. Also on the western shores are ophiolites with Troodos-type ores, representing blocks of oceanic crust thrust up onto the limestones and Precambrian rocks. Belts of ore-bearing ophiolites are also found in the central section of Newfoundland, as are volcanic rocks that contain Kuroko-type polymetallic ores. In the eastern part of the island are porphyry ores, apparently emplaced somewhat later in Newfoundland's history as oceanic crust was subducted beneath continental crust in the final closing of the ancient ocean. The pattern, as the investigators see it, is lead-zinc deposits in the west, then copper and iron ores, then overlapping bands of copper, lead, zinc, gold, and silver deposits, and finally occurrences of copper, molybdenum, and tin deposits in the east.

According to Strong, this pattern of mineral deposits with identifiable plate tectonic origins may well be common to the entire Appalachian-Caledonian chain. Limestones bearing lead and zinc are found from Norway to Alabama, always on the westernmost edge of the mountain chains. Also extending along the length of the chain are ophiolites with, in many places, Troodos-type copper and iron sulfides.

Known occurrences of polymetallic island arc deposits are more scattered, according to Strong, but appear to lie in the central and eastern portions of the Appalachians. Tin occurs in Alabama and Virginia still farther east. The mineral patterns constrain tectonic models for the Appalachians, especially by implying the existence of a southeastward-dipping subduction zone during the formation of the mountain belt, according to Strong. They also have implications for mineral exploration, he believes, since discoveries in Norway could lead to similar finds in Newfoundland and Tennessee or vice versa. Exploration of Newfoundland and eastern Canada has, in fact, accelerated during the past several years.

The new models of ore formation are far from complete and are still some distance from being completely accepted. Still newer ideas concerning the geochemical processes involved and the role of seawater are being proposed, and these will be the subject of a second article. But perhaps the most significant aspect of the emerging synthesis between plate tectonic theory and metallogeny is the prospect that, in a resource-hungry world, mineral exploration can increasingly be guided by a detailed understanding of how, and perhaps where, ores are formed and deposited.

Seawater and the Geochemistry of Ore Formation

Allen L. Hammond

After decades of government control and stability, the price of gold has in the past few years gone up dramatically. The higher prices have stimulated new interest in gold exploration. As it happens, research into the geochemical processes by which ores are formed has also led to new interest in gold deposits among economic geologists and to new theories of their origins. The combination promises to revolutionize gold mining.

What is happening in gold is in many ways characteristic of the rethinking going on in many aspects of ore geology and geochemistry ("A Conceptual Revolution Linking Minerals and Plate Tectonics," p. 95). Oceanographic studies, heat flow measurements, drilling cores, and a host of geochemical studies have provided evidence that the oceans interact with the earth's crust on a far more massive scale than previously supposed. This interaction, several investigators have proposed, is fundamental to the plate tectonic process and to the global cycling of volatiles and other elements, including metals, through the crust. Specifically, attention has been focused on seawater's role in extracting metals from cooling volcanic rock and the enhanced concentrations that result.

One important class of gold ores is now thought by some geologists to have originally been deposited as sediments on the sea floor by just such a process. Known as lode gold deposits, they are typically mined from quartz veins or lodes and, apart from the huge placer deposits in South Africa, are the most significant source of this precious metal. The richest ores are found in belts of ancient greenstone and schist rocks and include such mines as Kalgoorlie in Western Australia, Morro Velho in Brazil, the Ontario districts of Porcupine and Kirkland Lake in Canada, and the Homestake mine in South Dakota. Smaller but geologically similar deposits such as the Mother Lode in California occur in younger rocks.

If the new proposals are correct, gold was leached from newly formed volcanic rocks on the sea floor by seawater. The gold then was deposited along with some distinctive iron minerals as sea floor sediments and covered with more volcanic rocks. These rocks are of the type associated with island arcs, although whether that interpretation is correct for the older, Precambrian rocks is still open to question, and they often contain copper, lead, and zinc deposits as well. According to Richard W. Hutchinson of the University of Western Ontario in London, Ontario, the gold appears to be distributed rather evenly and at low concentrations throughout a layer of primitive volcanic rocks found toward the bottom of a volcanic pile. A variety of sediments and other geochemical indicators attest to the fact that the gold-bearing layer was formed in a submarine environment.

The veins or lodes themselves in many instances are now thought to have been formed as the gold-bearing volcanic rocks were later deformed and reheated; fractures were then filled with quartz or other materials and gold from the surrounding rocks. In this view the veins are artifacts of the geologic history of the gold deposits subsequent to their formation; the gold was concentrated into the veins by water circulating through the rock, repeating the process that occurred when the original ore was laid down. Hence the veins, the exclusive focus of mining up to the present, are thought to be a secondary feature of much larger, low-grade deposits. Because of higher gold prices, it may be possible to mine the low-grade ores using open pit or other high volume techniques, as is now done for certain copper ores, thus recovering all of the gold. Several mining companies, especially in Canada, are reported considering such an approach.

Other metal deposits appear to have undergone complex evolutions similar to that of gold. According to Bryan Fryer of the University of Western Ontario, seawater leaching of volcanic rocks and sediments may be important in forming initial concentrations of tin, tungsten, molybdenum, and silver, even though subsequent processes may determine where and in what form ore deposits actually occur. What seems to be emerging is recognition that it is easier to concentrate metallic ores in seawater than, as was long believed, in molten rock, although the presence of volcanism is presumed to be essential as a source of heat and, ultimately, of the metals themselves.

One model of the process is that proposed by John B. Corliss of Oregon State University. He suggests that seawater penetrates cracks in newly formed submarine volcanic rocks, setting up an extensive hydrothermal circulation driven by heat from the cooling rocks. Seawater interacts with the rocks, changing them chemically and releasing the metals. Chlorine from the seawater aids in leaching the metals by forming soluble metal-chloride complexes. The seawater then transports the metals up to the sea floor, where under appropriate circumstances they are precipitated to form metal-rich sediments. The hydrothermal circulation may penetrate deep into the volcanic material, perhaps 10 kilometers, extracting metals and altering the mineral composition of the rocks.

Similar suggestions have been made by William S. Fyfe of the University of Western Ontario and E. T. C. Spooner of Oxford. Fyfe, for example, points out that seawater supplies not only the chloride to help dissolve the metals but also sulfur (in the form of sulfates) and carbon dioxide, which become fixed in the upper layer of the ocean floor. As the brines return to the sea floor, sulfate helps to precipitate the metals.

Economic geologists have long known that metals are present in trace concentrations in a variety of volcanic rocks, but there has been and still is debate as to how they are concentrated to form ore deposits. There is evidence to suggest that hydrothermal circulations may indeed be the concentrating mechanism in many instances. Submarine volcanism occurs primarily at the mid-ocean ridges where new oceanic crust is formed and at island arcs above subduction zones. Oceanographers have noted that the conducted heat flow above mid-ocean ridges is often anomalously low, in agreement with the idea that much of the heat is convected away by hydrothermal circulation. Rocks dredged from the flanks of ridges show evidence of chemical alteration consistent with the hypothesis, and, according to preliminary results, so do cores obtained near the Mid-Atlantic Ridge last summer by the Deep Sea Drilling Project.

Several examples of active hydrothermal systems on the sea floor are

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known. The Red Sea, a center of incipient sea floor spreading, is perhaps the most studied of these. Since 1966 at least three U.S. expeditions and one West German team have visited the area. According to David A. Ross of Woods Hole Oceanographic Institution, brines as hot as 60°C were sampled near the sea floor. The circulation pattern seems to be downflow on the flanks, which are marked by thick salt deposits, and upflow near the center of the rift zone. The sediments on the sea floor, especially in one of several closed basins that are thought to promote precipitation, were enriched in copper, lead, and zinc to depths of 50 meters. The amount of metals present testifies to the effectiveness of the leaching process—on the 50-square-mile floor of the Atlantis II deep, for example, lie an estimated 3 million tons of zinc, 1 million tons of copper, nearly that much lead, and perhaps 5000 tons of silver, worth in all about $2 billion. Saudi Arabia and the Sudan, which border the Red Sea, have signed an agreement to share the sea floor resources, and an investigation of ways to process the ore is reported to be under way.

The closed basins and extremely high salinity of the Red Sea hydrothermal circulation make it something of a unique resource. The salinity in the open ocean, for example, could not build up as it has in the Red Sea basins; metal-bearing brines would also tend to be diluted and dispersed more once they reach the ocean. But investigators believe that similar processes do occur on the sea floor. French scientists last summer observed what they believe was a temporarily inactive hydrothermal system in dives along the Mid-Atlantic Ridge, and several research vessels have recently reported evidence of an active hydrothermal system in the Galápagos rift, a sea floor spreading center in the Pacific. Plans are under way to investigate the Galápagos site more carefully, including descending to the rift zone in submersibles to sample the fluids emerging from the sea floor and analyze their mineral content.

Other evidence of past hydrothermal systems comes from the polymetallic, massive sulfide ore deposits in ancient volcanic belts in Canada. According to R. H. Ridler of the Geological Survey of Canada, it is possible to distinguish a class of brine sediments, which he calls exhalites, associated with these ore deposits. These sediments form a distinctive pattern, with ore-bearing sulfides in the center of a belt, then carbonates on either side, and finally oxides on either edge. Ridler believes that the sedimentary pattern arises from variations in acidity, oxidation potential, and temperature in the area surrounding the vent of a submarine hydrothermal circulation. The less soluble species (which include the metal sulfides) precipitate nearest the vent, carbonates next, and finally oxides. Ridler has been able to trace exhalite patterns for hundreds of kilometers along mineral belts in Canada. These markers of past hydrothermal systems are now being used in exploration.

What is still unexplained, as far as the role of seawater in leaching metals from submarine volcanic rocks is concerned, is exactly what controls which metals are leached, and a number of theoretical and experimental investigations of the geochemistry of hydrothermal systems are under way. Nonetheless this process has been proposed as responsible for the Troodos-type ores found on Cyprus, which are associated with spreading centers; the young, massive sulfide ores associated with island arcs above subduction zones; and many older massive sulfide and precious metal deposits.

The interaction of seawater and crustal materials, and its implications for ore formation, may go beyond the presence of hydrothermal systems. Fyfe believes that chemical reactions involving seawater are not restricted to the area around spreading centers but continue as the oceanic plate moves. In particular, he believes that rocks in the upper portion of oceanic crust continue to change composition and to become more hydrated, locking in large volumes of water and other volatiles. Since most newly formed oceanic crust is eventually subducted and returned to the mantle, the plate tectonic process removes water from the oceans at a rate that, according to Fyfe, would deplete the oceans every 300 to 500 million years if it did not return. Thus Fyfe envisions a massive exchange of water and other volatiles between the crust and the hydrosphere which may be important in the production of volcanic and igneous rocks and their ore deposits above subduction zones. For example, melting of the oceanic crust being subducted is thought to be facilitated by the presence of seawater in the upper portion of the slab.

The ongoing reevaluation of ore formation processes in the context of plate tectonics is so broad that in some cases it is difficult to distinguish between it and more fundamental investigations of the earth's evolution. Some researchers, for example, are looking into the idea that the earth's oceans did not gradually evolve by degassing of the mantle but instead formed early in the planet's history and have been gradually diminished since then—a possibility suggested to them by mineral evidence. Thus whether or not the new metallogenic ideas improve our ability to find and extract metals, and they probably will, they promise to enliven geology for years to come.

Scientific Uses of Random Drilling Models

H. W. Menard and George Sharman

Success in petroleum exploration is chancy. In 1973 the chance of discovering an oil or gas field by drilling a wildcat hole in the United States was 1/7 and the chance of finding a million-barrel field or its gas equivalent was 1/54 (*1*). The relative importance of the factors that influence the chance of success has been difficult to evaluate, although it is known that success varies with the system of exploration, meaning the combination of theory and technology, that is used. In this article we develop a simple model of random exploration and apply Monte Carlo methods to generate possible histories of exploration for oil within the land area of the contiguous United States. The actual historical record of exploration is then shown to correspond in general form for long periods to a random search using a system of exploration with relatively constant effectiveness. The correspondence between the model and history suggests that the powerful tools of probability theory can be useful in analyses of future success in exploration, volume of petroleum reserves, and other matters of deep national concern. The beginnings of a probabilistic analysis of some aspects of petroleum exploration are presented here.

Model of Exploration

The model is based on the following assumptions: in a region of area S there is a fixed total amount of oil in undiscovered fields; the fields have a total horizontal cross-sectional area F and are located within the region by fixed, although not necessarily known, size and spatial distributions. One means of locating the oil is conducting a purely random search of the region. This method, after infinite effort, certainly locates the oil present and can be used as a standard for exploration success at intermediate times.

The probability P of discovering oil in a single unit of random search effort, a single drill hole, is

$$P = F/S$$

where F is the area of potential success (undiscovered oil) and S is the area of possible search. Measured in area per search effort, the rate at which F decreases is the same as the rate at which oil is discovered. The rate of discovery is, in turn, directly proportional to the probability of discovery. In mathematical terms, this leads to the differential equation

$$\frac{dF}{dE} = -k_1\frac{F}{S}$$

where E is search effort. Approximating S as constant, the equation has a solution of the form

$$F = Ae^{-\frac{k_1}{S}E}$$

an exponential relationship having a number of powerful and convenient properties. A similar result can be derived for an explicit class of equal-sized oil fields. Let N be the number of undiscovered fields, all of equal area f, distributed as in the previous case over the area S. The probability of discovery is

$$P = \frac{Nf}{S}$$

the rate of discovery, in terms of number of oil fields, is

$$\frac{dN}{dE} = -k_2\frac{f}{S}N$$

and the solution is

$$N = N_0e^{-k_2\frac{f}{S}E}$$

The exponential relationship has several mathematical implications. First, all derivatives and integrals are also exponential, differing only by a constant factor; rates and totals can be calculated. The rate of discovery is then

$$\frac{dN}{dE} = -N_0k_2\frac{f}{S}e^{-k_2\frac{f}{S}E}$$

and N_0k_2f/S is the initial rate at the time of N_0 undiscovered fields. Second, the exponential implies that with equal effort a constant fraction of the remaining undiscovered fields will be found. Third, exponential data, when plotted on a semilogarithmic graph, will fall on a straight line, the slope of which is proportional to the exponent factor. Fourth, that exponent factor consists of two parts. The first, k_2, is the number of trials in a unit of effort, equal to unity if the unit effort is the single drill hole. The second part is the probability of finding a specific single oil field, f/S. This is the relative target cross section, or R, the relative size of a single target compared with the entire search area. Finally, N_0, the initial number of undiscovered oil fields, is a fixed constant. In terms of the rate of discovery, the integral of that rate over effort must be the same constant. In graphical terms, the area beneath the curve for rate plotted against effort is that constant.

There are two broad directions in which the mathematical model may be applied. One is to the direct problem of assigning values to the variables and calculating a result for comparison or prediction in the real world. This entails selecting values of numbers and sizes of oil fields and the area being searched for the prediction of discovery rates. The other is the inverse problem, using the historic trends of discovery and exploration to assign values to the parameters. In particular, the value of R, combined with a discovery rate, can be used to estimate total undiscovered oil.

Two units of exploration effort are used in the ensuing discussion, the Hubbert unit (HU), 10^8 feet of exploratory drilling (*2*), or our own measure, 10^7 feet of new field wildcat drilling for oil (1 foot $\approx$ 0.3 m). Rate of discovery refers to the number of fields or area or volume of oil discovered per unit of exploration effort. Slope refers to the change in rate of discovery per unit of exploration effort. Specifically, on a semilogarithmic graph, this slope is directly proportional to R. Clearly, this is also a measure of the fraction of remaining oil fields discovered with each additional effort.

By comparing the R of a specific technology with that predicted for a random search, success of the technology can be numerically evaluated. Effective technology will be more successful than random search in locating undiscovered oil and will thus have a larger $R = f/S$. This can be interpreted as reducing the area of search or as enlarging the targets. In either case, the relative target cross section is increased. A numerical comparison of two technologies can be made by dividing the R's of the technologies by the R's of the equivalent random searches.

The effect of a hypothesis or technology

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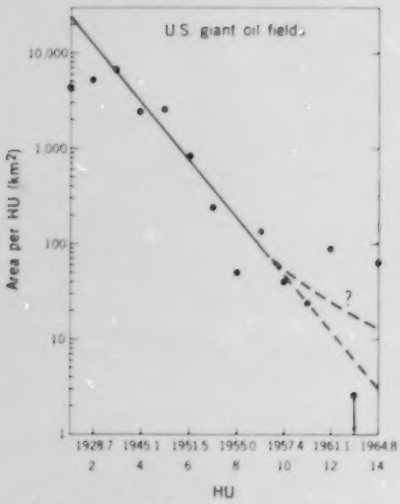

Fig. 1. Area of all giant oil fields discovered per Hubbert unit in the land area of the 48 contiguous United States. The trend is uncertain where lines are dashed. The upper dashed line is more consistent with data from other sources (*5*).

reducing the search area includes the possibility of excluding oil along with search area. Such a situation will be called a partially exclusionary hypothesis, such as searching only the white squares of a chessboard when, in fact, some fraction of the targets lies on the black.

Economics dictates the lower thresholds of field size and discovery rate—that is, when a field is too small or too hard to find to be economically productive. This article does not deal with economic fluctuations, but the model allows for calculating the difference in total recovery by varying technologies.

With a history of changing technologies, there are a number of possible configurations of slope and rate as well as transitions from one to another. Since the slope is related to f/S, one would expect different slopes for different size classes, the smaller classes having the lesser slopes. Likewise, a change from a less effective to a more effective technology should cause an increase in both rate and slope. There are possible configurations which conflict with the simple model and would point to such things as a partially exclusionary hypothesis. One such configuration would be a transition to steeper slope, indicating an increase in relative target cross section (effectiveness) without a corresponding increase in rate.

The effect of combined technologies, two different systems operating in the same region but analyzed in terms of the individual systems, would be additive and would produce inconsistent rates and slopes. In this case the individual rates would reflect the relative effectiveness of the particular technologies, while the slope would reflect the decline in undiscovered fields due to the discoveries of both methods. The region, considered as a whole with both technologies acting as one, would conform to the model. If, however, one of the competing technologies is operating under a partially exclusionary hypothesis, an abnormally low rate would be expected, since only a fraction of the total population is being targeted. Another effect would be to improve the effectiveness of a competing random search by eliminating some of the search area, thus improving the relative target cross section. The net effect would be transition from steep slope to that of random drilling as the more effective technology operating under an exclusionary hypothesis completes its search and thus depletes the undiscovered fields available to it.

In the following sections the history of oil exploration in the United States is examined toward two ends, testing the model and analyzing history in terms of the model. Since historic records have been conveniently broken down into size classes, the analysis is by class and in terms of the specific model dealing with numbers and rates.

Tests of the Model

Hubbert (*2*) states that the number of barrels of oil discovered per 10^8 feet of exploratory drilling has declined approximately exponentially. This conclusion is confirmed by analysis of the history of exploration for different sizes and types of oil fields by different methods. The American Association of Petroleum Geologists (AAPG) classifies oil fields by size in millions of barrels as follows: A, greater than 50; B, 25 to 50; C, 10 to 25; D, 1 to 10; E, less than 1; and F, wells originally completed as new productive fields but abandoned within the year. In addition, fields larger than 10^8 barrels are commonly called giants. The area, volume, and date and mode of discovery of giant oil and gas fields in the United States have been compiled by Halbouty (*3*, *4*). Our initial analysis is restricted to giant oil fields within the land area of the 48 contiguous states in order to have a coherent population and constant area. During the period of the first three Hubbert units the system of exploration changed rapidly and the rate of discovery increased (Fig. 1). However, from 1937.4 to 1956, the rate declined exponentially from 6800 km²/HU to an average of about 100 km²/HU. Evidently during this period the major factors that

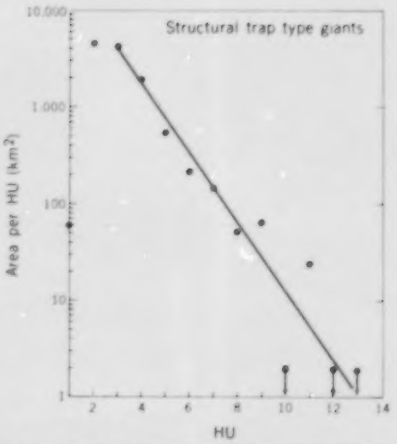

Fig. 2. Area of the structural trap type of giant oil fields discovered per Hubbert unit in the land area of the 48 contiguous United States.

influenced the success rate were those included in the probability model. This relationship is even clearer if the population is limited to giant structural traps, which have a smaller range of sizes than the quite different stratigraphic traps (Fig. 2).

The probability model also predicts both the decline of success in finding smaller oil fields during the period from 1945 to 1966 (*1*) (Fig. 3) and the fact that the rate of decline (slope) tends to diminish with field size.

Some of the factors that influence the chance of success in drilling can be isolated by consideration of the discoveries per unit effort of different modes of discovery. With regard to giant oil fields, discovery by surface seeps was most successful in the first Hubbert unit and declined exponentially to near zero four units later (Fig. 4). Surface geology had a peak of success during the second Hubbert unit and approached zero five units later. The success of subsurface geology and geophysics peaked in the third Hubbert unit and declined exponentially to near zero four and five units later, respectively. The slopes of the curves are essentially the same for all methods but the maximum rate of success was achieved by surface geology—the first application of science to exploration. Thus, each method of discovery was equally successful in sampling a dwindling population of giant oil fields. Each method quickly found the fields that it was capable of finding. Each group of fields successively approached exhaustion until about 1950, when none of the methods of exploration had any more cream to skim. At that time an inflection in the discovery rate curve occurred, and since then it has declined very slowly because giant discoveries are few.

The rate-of-discovery curves for smaller oil fields also tend to be inflected in the

1950's, although the amount of the inflection decreases for smaller field sizes (Fig. 3). For classes C and D it appears that the transition is gradual, which can be interpreted according to the probability model as indicating that two systems of exploration—for example, random and scientific—were operating simultaneously. Indeed, the inflections in these curves give strong evidence that in the 1950's the system of exploration for oil in the land area of the 48 contiguous states decreased markedly in average effectiveness.

In this analysis we have lumped all industry together for lack of appropriate data to make a separation. However, there are striking differences in the operations, success, and possibly even goals of exploration systems in use by major and independent oil companies and investment funds (*5*). This can be seen in the fact that from 1969 to 1973 the independents drilled 22,792 new field wildcats and the majors drilled only 2,770 (*1*). A significant difference is also shown by the discovery rate, in that the independents required 46.6 wells to find one new field while the majors needed only 19.4 wells. The contrast is even more striking when the size of the fields is considered, because the independents found most of the little fields and the majors found most of the big ones. Thus, although the majors drilled only roughly 10 percent of the wells, they found roughly 60 percent of the oil. It is possible that part of the change in the rate of discovery in the 1950's reflects an increase in the proportion of drilling by independents, as the majors were beginning to obtain cheap foreign oil in increasing volume.

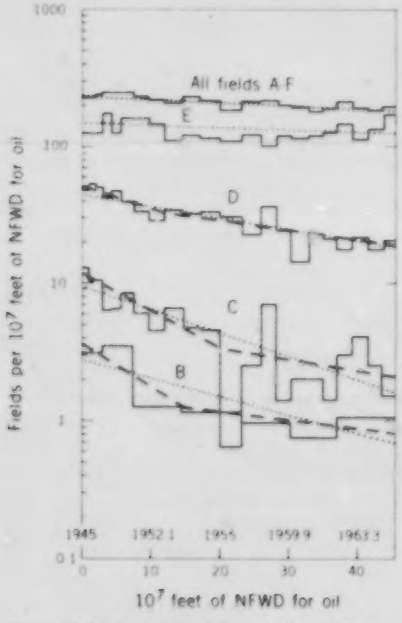

Fig. 3. (Solid lines) Number of fields of different sizes discovered per 10^7 feet of new field wildcat drilling (NFWD) for oil in the land area of the 48 contiguous United States. (Dashed and dotted lines) Interpretations of trends.

Success of Exploration

It is possible to calculate the probability of the actual history of oil exploration and compare it with other possible histories. Thus, a technique exists for determining the success of exploration systems, comparing them with purely random drilling.

In order to make a comparison it is necessary to know the discovery history of a class of oil fields, the total area being explored, and the total area of the fields. The last of these is the most difficult to assess with reasonable accuracy. Two pertinent bodies of information are available. The area of giant oil fields is given by Halbouty (*3*) and the trivial rate of discovery at present indicates that this closely approximates the total area. For smaller fields, the discovery rate can be extrapolated to infinite effort to give the total number, which can be converted empirically to area or volume.

We begin with the discovery of giant fields (Figs. 1 and 2). Halbouty's data were reorganized to give the history of discovery per Hubbert unit by area (and volume). Thus it was established, for example, that the 3947th through 4048th square kilometers of giant fields discovered were in the Midway-Sunset field in California. A computer was programmed to simulate random search in a total area of 4,700,000 km^2 (*6*) for a total area of giant oil fields of 23,455 km^2. Numbers were selected between 0 and 4,700,000 according to a random number generator. If one was selected between 0 and 23,456, it was printed in the output. A Hubbert unit was taken to be 20,000 tries, equivalent to 20,000 wildcat holes 5,000 feet deep. The printout identified a particular square kilometer of oil field discovered by a random hole, and this could be related to a particular oil field of known area and volume by comparison with the reorganized historical data.

The historical record is that the first Hubbert unit discovered 4.6×10^9 barrels of oil with an area of 4,100 km^2. The average of ten computer runs equivalent to the first Hubbert unit was 22.7×10^9 barrels and 13,780 km^2, with a range between 17.5×10^9 and 26.0×10^9 barrels and 12,600 and 14,600 km^2. The random search was four to five times more successful than the early gropings of the oil industry. The only substantial error in the calculation lies in the simplifying assumption that each well was 5,000 feet deep and thus that a Hubbert unit included only 20,000 wells. This is a fair approximation for the more recent Hubbert units after the fourth, but the average depth of the first unit may have been only 500 feet (*2*). If so, the first Hubbert unit included 200,000 exploratory wells; the computer program would have discovered much more oil with the additional tries. There is a compensating fact in that, historically, some fields were discovered by holes deeper than average, perhaps even deeper than 5,000 feet. However, the larger fields were discovered by the computer repeatedly on each run. Many would have been found by reducing the number of holes and varying the depth randomly within a desired range. With these uncertainties, the program was left unchanged, although it appears to be biased in favor of history.

The reason that random drilling is relatively successful is that the probability of finding giant fields is quite high because many have a large area. For example, historically the largest field by far, East Texas, was not discovered until 1930, in the third Hubbert unit. On nine of ten runs the computer program found the 5.1×10^9 barrels of East Texas by 1902, in the first Hubbert unit, because the area of 567 km^2 is so large. Indeed the probability is

$$1 - \left(1 - \frac{f}{A}\right)^n = 0.91$$

where f is the area of the field (5.67×10^2 km^2), A the area of U.S. sedimentary basins (4.7×10^6 km^2), and n the number of holes per Hubbert unit (2×10^4)—or just nine to one in favor of finding in a single Hubbert unit.

The historical procedures of the American oil industry clearly were not favorable to the discovery of large oil fields, although that might be thought of as the objective. Perhaps it was not entirely chance that

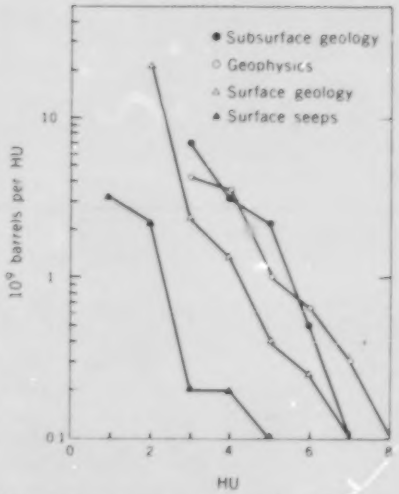

Fig. 4. Rate of discovery of giant oil fields per Hubbert unit by mode of discovery.

even in the historical record the East Texas field was discovered by random drilling. Very roughly 300,000 exploratory holes had already been drilled in the sedimentary basins of the United States. The probability of not finding this field with that many random tries is 2×10^{-16}. There are many possible explanations for this bad luck. The important point here is that exploration systems are not uniformly successful in achieving different objectives. What may be reasonable and traditional for some times and objectives may be quite irrational for others.

The random searches of a computer in successive Hubbert units may be compared with history in two useful ways. One procedure is to determine what a random search finds in the first Hubbert unit and reset the program to search for what remains in each successive unit. In some ways a more interesting approach is to reset the computer program after each Hubbert unit by subtracting the area discovered historically during that unit. This approach makes it possible to see how closely the discovery of giant fields corresponds to a random search for the targets that were still undiscovered at a given time. Ten computer runs have been compared with history (Fig. 5). All were far more successful than history in the first and second Hubbert units. By the third unit, ending in 1937.4, the historical rate of discovery was just what would have been achieved by a typical random search. From then on history did not differ significantly in its rate of discovery from a random search. Sometimes, as from 1937.4 to 1945.1, it was in the lower range of discovery rates and at other times, such as the early 1950's, it was on the high side, but it was always within the range of the computer runs.

This whole history can be viewed in terms of the mode of discovery. In the earlier years, when the mode was principally by random drilling, seeps, and surface geology, the rate of success did not match the computer. The introduction of subsurface geology and geophysics as the dominant modes of discovery managed to bring the success rate up to what would have been achieved by random sampling.

In terms of oil volume rather than oil area, historical discoveries compare more favorably with chance targeting (Fig. 6). During the period from the first to the fifth Hubbert unit, 1902 to 1948.9, the historical discovery rate was greater than that of any of the ten random searches and as much as twice their average. Before and after that period, however, the historical successes were within the range of the random searches.

In historical perspective, the American oil industry has had mixed success in finding giant oil fields. With regard to finding the less prolific giant fields with large areas, it has never been as successful as an average random search. With regard to the more prolific giant fields with small areas, its actual targets, it was more successful than any of ten random searches during the period when geology and then geophysics was used to find a still abundant population. Since then it has been only slightly more successful than the average random search. The high point of the search for giant fields was in the fourth Hubbert unit, when the volume of oil discovered was more than twice the average volume found in ten random searches, even though the area found was less than average. That was a period when a profusion of 100- to 200-million-barrel fields were found over salt domes in Louisiana, which were precisely and easily located by geophysics. In such circumstances the industry did far better than average random drilling. Otherwise it did not.

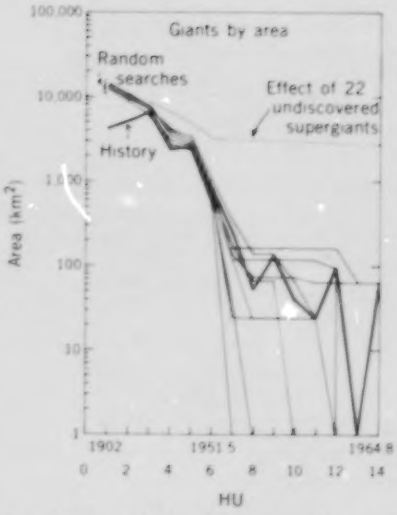

Fig. 5. Historical rate of discovery of giant oil fields, by area, compared with ten random searches for the fields historically remaining at the end of each Hubbert unit. If 22 extra supergiant fields exist, the probable average discovery rate of random searches would exceed the historical record 50-fold.

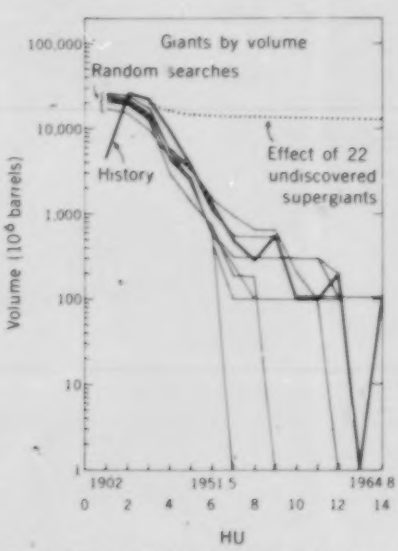

Fig. 6. Historical rate of discovery of giant oil fields, by volume, compared with ten random searches for the fields historically remaining at the end of each Hubbert unit. If 22 extra supergiant fields exist, the probable average discovery rate of random searches would exceed the historical record 50- to 100-fold.

The effectiveness of exploration systems in finding nongiant fields can be assessed provided the total number and average size of fields in each class and the area of search are known. Consistent data on historical discoveries of all sizes of fields are available from 1945 to 1966 (Fig. 3). The population as yet undiscovered in 1966 can be determined by extrapolating the discovery rates to infinity. The remaining unknowns are the number and size distribution of fields discovered before 1945, which can be estimated, perhaps only crudely, from analysis of other rate curves. The curve for "wildcat producers" (*1, 7*) is roughly parallel to that for giant fields during the critical interval from 1945 to 1955. The rate of discovery per Hubbert unit for the total and for each class of field can be adjusted to the total number of fields discovered before 1945 and an approximation of the giant field and wildcat producer data. Combining all the estimates from time zero to infinity gives a population of 243 giants (approximates class A); 449 class B; 998 class C; 4,700 class D; and 42,100 class E (Table 1). The larger the fields the earlier the median field was discovered.

The relationship of volume to area of oil fields in the Denver-Julesburg Basin, Colorado, is known (*8*), and a similar relationship can be constructed for the dead or moribund oil fields of California from the data of the California Division of Oil and Gas (*9*). The average for the two regions reasonably approximates the expected relationship that area varies as the volume (V) to the 2/3 power. However, the range of sizes in each class is very large (Table 1).

The area of all nongiant fields in the contiguous United States can be estimated by subtracting the area of giant oil and gas fields from the total area of all sizes. When the remainder is compared with the size-frequency distribution for nongiant fields, it appears that the class sizes of the Denver-Julesburg Basin are a reasonable approximation of those in the whole United States.

The remaining uncertainty is the area being searched, and in 1945 and later this is taken to be 2,600,000 km², the most ex-

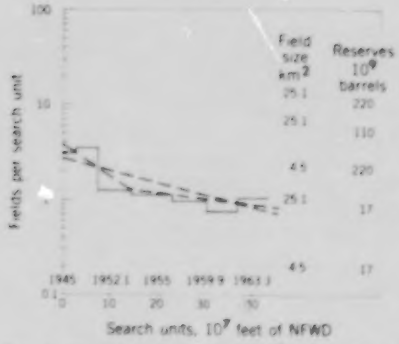

Fig. 7. Historical discovery rate of class B oil fields compared with random searching for different total populations (reserves) and field areas. (Solid line) Historical discovery rate. (Dashed lines) Two interpretations of the historical trend. (Dotted lines) Average discovery rates for random computer searches.

plored and most productive area of sedimentary basins (*10*).

A computer program incorporating the data on number, target size, and area of search was used to make the same random searches as for giant fields. Numerous combinations of number and target size were investigated and printed out in terms of number of discoveries per search unit. Some of the results appear as averages in Fig. 7, which compares some of these computer searches with history.

For class B fields, the average slope of the historical success curve is steeper than that for any of the computer searches. This indicates that industry has been more successful than random search in finding this class of field. However, there appears to be an inflection in the curve, and the slope after about 1950 is within the values for random searches for fields the size of the California or Denver-Julesburg ones. The slope corresponds to a random search for fields with an area of 11.7 km². Industry has already found most class B fields (Table 1).

The discovery of class C fields bears about the same relationship to a random search as that of class B fields. The average slope indicates far greater effectiveness than random drilling, the population has been depleted, and the inflected slope indicates effectiveness only slightly greater than that of a random search since 1955. The class D and class E fields are not so depleted. For class D, the inflected slope is hardly steeper than that for a random search, and yet the discovery rate is at least twice that of the most successful type of random search. Perhaps the inflection is not real and the slope remains constant. If so, the population will be depleted relatively rapidly.

The record for class E fields is that the slope of the discovery rate curve is constant and steeper than for a random search. The remaining population is a large fraction of the original one, and therefore the effective industry is about 70 times as successful as ineffective random searches.

In sum, for oil fields of classes B to E, actual oil exploration has been more effective than a random search. Its successes have effectively depleted not only giant fields but also class B and C fields. Smaller fields are not so depleted, and they are located by industry far more successfully than by a random search.

Undiscovered Oil Fields and Reserves

There are at least five different methods of estimating the volume of undiscovered hydrocarbon resources (*11*). One of the methods was pioneered by Hubbert (*2*). Extrapolating the historical data on the rate of discoveries per exploration unit according to the equation of change in the rate, he determined that in 1966 the undiscovered recoverable oil in the United States, including the continental shelf but exclusive of Alaska, was 71×10^9 barrels. Essentially the same method is used here, but with the refinement that the distribution of oil field sizes is also determined.

Although the giants are mainly gone and the intermediate fields are following, a very large number of small fields remain undiscovered. However, infinity is a long time to explore for oil, and it may be worthwhile to examine the more modest discoveries predicted for drilling 140 more units of 10^7 feet of new field wildcat holes. At present rates that would be the year 2020 and, by exponential extrapolation of the uninflected rate of discovery curves, 14,300 fields will have been discovered. Very few class A or giant fields will be discovered; in the other classes the numbers discovered will be: B, 21; C, 41; D, 890; and E, 13,400. The numbers are not too different for the inflected curves in this brief interval.

Converting the area or number of fields to volume of recoverable oil involves considerable uncertainty. For the older discoveries Hubbert (*2*) calculates a multiplier of 5.8 to the estimates of new discoveries at the end of the first year to obtain the ultimate amount recovered including secondary recovery and field extensions. For 1959, however, the increase after 6 years was only 20 percent, and a reevaluation of all AAPG data since 1943 indicates that after 9 years the original estimates were good within +60 percent and −30 percent (*12*). In recent years the original estimates have tended to be high (*13*), which further complicates the problem. These inconsistencies are the result of some combination of actual increases of oil discovered and differences in methods of estimating volumes. The analyses of the data used here in predicting the number of undiscovered fields indicate that the average of the volumes as originally estimated is essentially correct, particularly for the smaller fields, which will predominate in the future.

The accepted average size in the year of discovery for various classes of fields is expressed in millions of barrels as follows: B, 37; C, 17; D, 3; and E, 0.13. Accordingly, the undiscovered reserve of oil in new fields in the land area of the contiguous United States lies between 14×10^9 barrels, indicated by the constant decline curves, and 17×10^9 barrels, indicated by the inflected curves. About two-thirds of the oil is in class E fields, which are not considered economically significant.

It is difficult to obtain estimates of undiscovered reserves which are completely comparable to those given here because offshore and Alaskan areas are usually added to the past and future discoveries in the United States, and oil and gas equivalents are not separated. However, there are two recent estimates of the amount of oil and natural gas liquids still undiscovered in the land area of the contiguous states. One, by Mobil Oil Co., is 13×10^9 barrels and the other, by the U.S. Geological Survey (USGS), is 110×10^9 to 220×10^9 barrels (*11, 14*).

If the overall prospect for domestic oil discoveries appears bleak, the economic prospect is far bleaker. This is because two-thirds of the oil is in class E fields. Moreover, not all the oil can be found in less than infinite time, and eventually it will become uneconomic to preserve the

Table 1. Size-frequency distribution of oil fields discovered in 1945 to 1966 and estimated equivalent distributions from the beginning to the end of exploration.

Class	Number of fields				Area (km²)		
	Before 1945	1945–1966	1967– ∞	Total	Denver-Julesburg	California	V[illegible]
A (giants)	211	32	Few	243+			
B	328	64	57	449	25.1	4.5	10.5
C	690	196	112	998	13.4	2.8	6.2
D	2,240	1,324	1,140	4,700	3.6	1.0	1.9
E	5,150	5,828	31,100	42,100	0.6	0.2	0.4

exploration systems just when they need to be expanded to continue successful searching. Consider no farther ahead than the 1960's. Probable discoveries in that decade are 10 class B, 21 class C, 210 class D, and 2200 class E fields. The probable annual rate of discovery is about 2×10^9 barrels, which is equal to only a few weeks of consumption even at present rates. This small quantity will be concentrated in minor fields that are relatively difficult to find and expensive to develop. Accelerated drilling could bring a surge of successes at any time compared to these estimates, but it would only hasten the end.

Trade-off Between Exploration Success and Quantity of Undiscovered Reserves

The probability theory of oil exploration provides a trade-off between the discovery rate of an exploration system and the quantity of undiscovered oil. This makes it possible to determine the implications of seemingly unrelated estimates about resources.

Consider, for example, the specific hypothesis of Moody *et al.* (*15*) that in 1968 25 to 28 supergiants of 5×10^8 barrels or more remained undiscovered in North America. The undiscovered fields are assumed to have sizes that are spread throughout the range of known ones larger than 5×10^8 barrels and to be evenly distributed within the regions where the known ones have been found. Accordingly, there were 22 undiscovered supergiants with an average area of 168 km^2 in the land area of the contiguous United States. If so, the computer program should be adjusted to add 3700 km^2 of oil fields to the total remaining after each Hubbert unit. At first this makes little difference, but as the undiscovered fields of the historical record decrease, the hypothesized addition looms ever larger. By the end of the fourth Hubbert unit the average random search would be about three times as successful as history (Figs. 5 and 6). After the eighth unit in about 1955, a random search would be roughly 50 times more successful than the oil industry.

The implications can also be determined by calculation. The probability of discovering one of these giant fields by random drilling is 3,700 km^2 divided by 2,600,000 km^2, where the denominator is the area of the more promising and better explored sedimentary basins. Thus the chance of discovering one field with a single random hole is about 1/700. In order to obtain a fifty-fifty chance of finding some field it is necessary to drill only 488 holes. A total of 57,200 holes would give a fifty-fifty chance of finding all of them. In terms of a Hubbert unit drilled not just to 5,000 feet but to 10,000 feet per hole, the chances are about a million to one in favor of finding at least one field. These calculations lead to two plausible conclusions that are compatible with the fact that new giant oil fields have not been discovered since 1968 at the indicated rates: either the hypothetical oil fields do not exist, or the system of exploration is drilling in the wrong places. This second possibility has been seriously advanced by several eminent experts on petroleum exploration. Hubbert (*16*) refers to a decline in the ability to find oil fields as "in part the result of our inflexibility with regard to our geological ideas concerning where oil *ought* to be found. In fact, it is entirely possible, physically, that a large class of undiscovered fields may exist which, on the basis of present geological premises, would be discovered only by accident or not at all." Halbouty (*3*, p. 1150) proposes that many stratigraphic traps can be found "but only if geologists direct these methods and their thinking *toward* them, not around them. Only by looking *purposely* for such traps will giant fields continue to be found."

Another example of a trade-off is based on the USGS estimates of undiscovered oil reserves. The volume of oil in undiscovered fields of classes B to E as of 1945 has been calculated. To this is added the excess of the USGS estimates over the present estimates of reserves in 1974. Volume is directly convertible to area, and the new area is distributed in some way among the classes. Consider classes B and C after a division of the additional oil in proportion to future discoveries per class (Table 1). The average area of the undiscovered fields is taken to be equivalent to that of the same class in the Denver-Julesburg Basin. If the reserve remaining in 1974 was 220×10^6 barrels, a random search beginning in 1945 would have found about 20 times more class B fields than were found. Even with the minimum estimate of 110×10^6 barrels, a random search would have discovered oil at ten times the historical rate. If the undiscovered fields in each area are the same size as the discovered ones, or even as small as those in California, the estimates of the USGS require that the oil industry since 1945 has been much less successful in finding class B fields than a random search. The same conclusion follows from analysis of class C fields.

Perhaps the extra oil is not proportionally distributed among the classes but is instead concentrated in smaller fields which industry is less apt to seek. Assume that the excess is divided equally between classes D and E. If so, a random search beginning in 1945 would still have been more successful than the historical record. Perhaps all the oil is in class E fields. Once again, history fails to match a random search.

According to the probability model of exploration, an exploration system can be less successful than chance only if it contains some flaw that causes it to deliberately search in the wrong places. The trade-off is that either the USGS estimates are unrealistically large or the oil industry has gone astray for the last quarter of a century.

Conclusions

Successful oil finding is influenced by chance as well as social, economic, scientific, and technological factors (*17*). The history of success in petroleum exploration in the United States indicates that for long periods most of the factors have tended to balance each other and statistical fluctuation and progressive depletion of a finite resource have been the dominant variables.

An industrial exploration system is aimed at targets which could also be hit without aiming. Thus, the success of the system is determined not by its discoveries but by how much it exceeds what might have been achieved by random drilling. Judged by the historical record, industry has been successful in finding small targets but less so in finding large ones (*2*). The most plausible explanation of this is that industry has selectively, if inadvertently, aimed at the small targets. This, in turn, reflects in some way the factors that influence the exploration system.

The goals of the exploration system are also complexly determined; certainly they have never been limited to just finding oil. At the minimum the target had to be conceived as a commercial quantity of oil, under a property controlled by the producer, and recoverable at a rate that gave an appropriate return on capital. With those goals it might be entirely reasonable for an exploration system to aim at small targets. However, quite different goals now exist in the world. The governments of many large countries are not concerned about the location of an oil field because they control all the mineral rights anywhere in the country or in some region such as the continental shelf. Likewise a quick return on capital may not be as important as an inventory of energy resources to serve as a guide for national policy. With these changing goals in mind, it may be appropriate to reconsider the relevance of the exploration systems which have brought the discoveries of the past. An apparently venturesome fractional investment in a search for subtle giant stratigraphic traps (*3*) or hydrodynamic

ones (*16*) may actually be a prudent course for many large countries. The mean random search of the sedimentary basins of the United States would have discovered more than 227 barrels of oil per foot of exploratory drilling for the first 10^9 feet. Venturesome scientific targeting, such as drilling on a grid, might be comparably successful in a relatively undrilled large country or region.

The future for oil exploration in the land area of the contiguous states appears relatively bleak. With existing exploration systems, a search effort will discover less and less. A significantly improved technology, if one can be devised, will meet with increased success briefly but will only hasten the exhaustion of domestic reserves. Moreover, about two-thirds of the oil undiscovered by existing exploration systems is probably in small traps which are difficult to target. In the United States, therefore, there will be a growing need for ever more detailed and exhaustive searches. Presumably there will also be need for more and more earth scientists until the expanding exploration becomes economically or energetically profitless.

The methods we have used in this study predict that the undiscovered reserves of oil in new fields in the land area of the contiguous states are only 14×10^9 to 17×10^9 barrels, about the same as the Mobil Oil Co. estimate. Moreover, at present rates of drilling the discovery rate in the 1980's will average only 2×10^9 barrels per year. This is equal to a mere few weeks of consumption even at present rates. The methods permit an evaluation of the probability of much larger reserves as predicted by the USGS. If the large reserves exist, the petroleum industry is far less successful than it would be if it just drilled holes at random. This is only possible if the exploration system has inadvertently been designed to search in what are now the wrong places. A similar analysis of a hypothesis that many giant fields remain undiscovered leads to the same conclusion. With regard to national energy policy, most of the undiscovered oil of the future probably can be expected only from Alaska, the continental shelf, or imports.

There is one possible basis for optimism, namely the hypothesis advanced by some geologists that the oil industry is no longer searching in the right places. If the decline curves merely apply to an exclusionary hypothesis, they give little information about the reserves in the area being excluded. With the data available to us we are unable to test this idea by separating the decline curves for random and aimed targeting but we believe that it may be possible to do so.

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6. The area is that of outcrops of sedimentary rocks in the 48 contiguous United States according to I. H. Cram [in *Future Petroleum Provinces of the United States—Their Geology and Potential*, I. H. Cram, Ed. (American Association of Petroleum Geologists, Tulsa, Okla., 1971), vol. 1, p. 1]. The computer knows just enough geology to avoid drilling outcrops of igneous or metamorphic rocks.
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18. We have benefited from comments on a manuscript draft and discussions with J. B. Coffman, W. R. Eckelmann, H. Gould, and R. Howe of Exxon Corp., or its affiliates. We also received useful ideas in a conference with members of the U.S. Geological Survey at Reston, Va., and in written comments on a draft of the manuscript from A. L. Clark, B. F. Grossling, and D. A. Singer. This work was supported solely by the general funds of the Institute of Marine Resources and Scripps Institution of Oceanography, University of California.

Technological Insurance Against Shortages in Minerals and Metals

The Bureau of Mines has under way programs on recycling and more economical production of metals.

Ralph C. Kirby and Andrew S. Prokopovitsh

The United States is faced with the challenge of producing more minerals and metals from lower grade resources.

The United States has an insatiable appetite for minerals. With but 6 percent of the world's population and only 6 percent of the world's land area, we consume 23 percent of the world's nonenergy minerals. In the last year and a half this pattern of usage has not changed appreciably. Stated in other terms, in the last 35 years we in the United States have consumed more minerals than all of mankind from the beginning of time up to about 1940. The forecast for the future is that in the next 25 years our mineral needs may triple. The supply is deteriorating steadily as demand increases, domestic high-grade ores are being used up, and other nations compete with us for world supplies. To meet this challenge requires a strengthening of U.S. metallurgical processing research and development efforts.

The nation has been a net importer of minerals since World War II. By the year 2000, we may be forced to get more than half of our nonfuel mineral requirements from foreign sources unless we move to increase their availability from domestic sources.

The United States is dependent on imported manganese, chromium, aluminum, platinum, and many other minerals and metals (Fig. 1). For example:

1) We import 90 percent of our aluminum needs, and yet there are unlimited

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aluminum-bearing resources in the United States in the form of clay and anorthosite. Economically viable processes for recovering the alumina from these resources must be developed to reduce our reliance on imported bauxite.

2) We import 25 percent of our iron and steel requirements, and yet billions of tons of nonmagnetic taconites lie virtually untouched.

3) We import 85 percent of our fluorine requirements, and yet in the processing of phosphate rock we discard more fluorine than we use.

4) We import about 70 percent of our nickel, gold, and silver, and yet we have domestic resources of these metals which also await the development of viable technologies for their exploitation.

5) We import 97 percent of our rutile requirements, and yet we have large deposits of ilmenite which could easily supply our titanium metal and TiO_2 pigment needs.

To overcome these dependencies, in part at least, it will be necessary to make real innovations and take major steps forward in exploration, mining methods and ore transport, processing low-grade resources, improved materials development, substitution and use, and secondary resource recovery. This will result in more efficient use of our resources and also will help ensure an adequate supply of mineral resources in the future.

Bureau of Mines Program

The metallurgy activity has been an integral part of the Bureau of Mines since its formation when Congress established in the Department of the Interior a bureau of mining, metallurgy, and mineral technology. The need for this work has been confirmed by subsequent legislation. To execute the primary charter, the general purpose of the current metallurgy program of the Bureau of Mines is to help improve the nation's minerals and metals posture. Research and development are directed toward providing the scientific and technical information necessary to encourage and stimulate the nonfuel minerals industry to make the expeditious advances in technology that will encourage the private sector to produce an adequate and continuing supply of mineral raw materials at acceptable material and energy costs, and with a minimum of waste and environmental degradation.

The Bureau of Mines metallurgy program is oriented toward the accomplishment of the following objectives. Under "Advancing Minerals Technology," research is conducted that will result in major improvements in metals and minerals processing technology. "Minimizing Mineral and Metal Needs" covers research that will yield high-quality materials with improved performance and with increased service lives, which will result in more efficient use of our mineral resources. The objective of "Secondary Resource Recovery" is developing methods for recovering metals and minerals from mineral and industrial wastes, for upgrading and refining these metals and minerals, and for developing uses for them.

Much of the metallurgy program addresses the problem of treating lower grade ores, recycling, and better utilization of resources. It reflects, too, the dominant influence of the supply situation, the patterns of energy consumption, and the impact of environmental constraints. Significant among the needs that this program is designed to satisfy are the development of (i) economic methods to recover minerals and metals from ore bodies of progressively lower grade, (ii) improved materials and metals that have reduced rate of deterioration and are suitable for use with high temperatures, in corrosive environments, or in other adverse conditions encountered in chemical and metallurgical applications.

Fig. 1. Imports supplied a significant percentage of the total U.S. demand in 1974.

MATERIAL	FORMULA	% Al	% Al_2O_3	TONS/TON Al
ALUMINA	Al_2O_3	53	100	2
BAUXITE		25	47	4
Boehmite	$Al_2O_3.H_2O$			
Diaspore	$Al_2O_3.H_2O$			
Gibbsite	$Al_2O_3.3H_2O$			
CLAY		20	38	5
Kaolinite	$Al_2O_3.2SiO_2.2H_2O$			
SHALE	Impure clay	15	28	7
ANORTHOSITE		14	27	7
Albite	$Na_2O.Al_2O_3.6SiO_2$			
Anorthite	$CaO.Al_2O_3.2SiO_2$			
ALUNITE	$K_2SO_4.Al_2(SO_4)_3.4Al(OH)_3$	20	37	5
DAWSONITE	$NaAl(OH)_2CO_3$	19	35	5

Fig. 2. Alumina content of selected resources.

(iii) new or improved methods for preventing pollutants in the off-gas streams, liquid effluents, and waste products of mineral processing plants; (iv) new nonstandard innovative methods of recovering metals and minerals that maximize efficiency and minimize pollution; (v) metallurgical processes that use less energy or use low-cost sources of energy; (vi) improved technology for increasing the proportion of our nation's minerals supply obtained through recovery and utilization of the valuable constituents in currently discarded scrap; and (vii) wider use of mineral materials that are abundant, and origination of substitutes for scarce minerals.

While the metallurgy program is designed primarily to meet long-term national needs, it is also concerned with current problems of broad scope that affect the nation's immediate mineral position. In many instances, industry, as groups or as individual companies, participates in cooperative cost-sharing projects to accelerate the work.

Advancing Minerals Technology

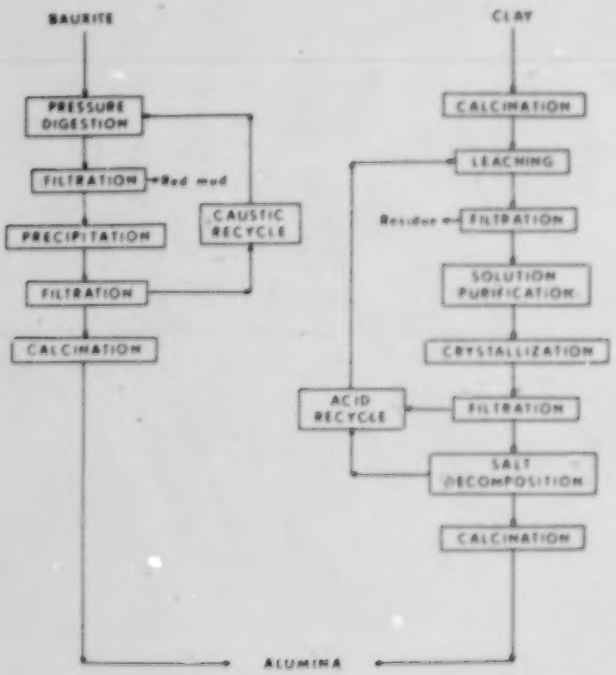
Nonmagnetic taconite iron ores. The United States in the past was fortunate in having a large supply of high-grade direct shipping iron ore in the Lake Superior District deposits, the major sources of iron ore for the United States steel industry. These high-grade iron ore deposits, containing about 55 percent iron, eventually gave out and it became necessary to turn to the taconite ores which contain only about 35 percent iron. Magnetic taconites became the major domestic source of iron but were limited in extent and imposed limitations on expansion of production. To assure adequate supplies of iron ore to meet expanding needs in the years ahead, research was conducted to develop the technology for concentrating the much larger domestic resource of nonmagnetic taconite ores.

The Bureau of Mines attention to iron ore research has now focused on the vast nonmagnetic taconites of the western Mesabi range in Minnesota. In the past year, experimentation was started on an initial bulk sample of 350 tons of these taconites. The research included a pilot plant for flotation studies of the type and scale leading to the Tilden, Michigan, plant of the Cleveland Cliffs Iron Company (*1*).

Alternative technologies for processing these resources, alone or in combination, are: (i) selective flocculation cationic flotation; (ii) reduction roasting magnetic separation; and (iii) wet high-intensity magnetic concentration. Pilot plant feasibility studies incorporating these three are planned for the roasted products so that economic comparisons can be made between the competing processes.

Aluminum. Although the United States produces about one-third of the world's aluminum, it must import 90 percent of the raw materials needed. Bureau of Mines forecasts of the aluminum situation show that U.S. demand for aluminum in the 1960's increased at an average annual rate of 9.4 percent, with a projected long-term growth rate of 6.5 percent, higher than that of any other metal. While there is no worldwide shortage of bauxite, the United States must increasingly compete with other industrialized countries also seeking reliable sources of supply at acceptable prices. The drastic increase in bauxite mining taxes imposed by Jamaica about 2 years ago, subsequent similar actions by other producers, and strong trends toward nationalization of mining operations add to the uncertainty of U.S. supplies. Furthermore, bauxite-producing countries are increasingly demanding that alumina (Al_2O_3) plants and aluminum (the free metal) smelters be built in their own countries in order that they may export intermediate or end products of higher value and thus increase their revenues and provide jobs locally.

From the standpoint of national interest, there is thus an urgent need to advance a technology that will allow the United States to make use of its ample domestic resources for aluminum production. For the long term, our reserves of bauxite are essentially negligible. On the other hand, there were, according to a 1967 report (*2*), more than 160 billion tons of alumina in the United States in sizable deposits of anorthosite, clay, laterite, shale, and low-grade bauxite (*1*). This report did not cover other resources that could become important to domestic alumina production—alunite, dawsonite associated with oil shale, and coal mine wastes. New, large deposits of alunite, overlooked in previous explorations, have recently been reported. Dawsonite's potential rests with the development of oil shale as a major energy source, and doubling coal production will



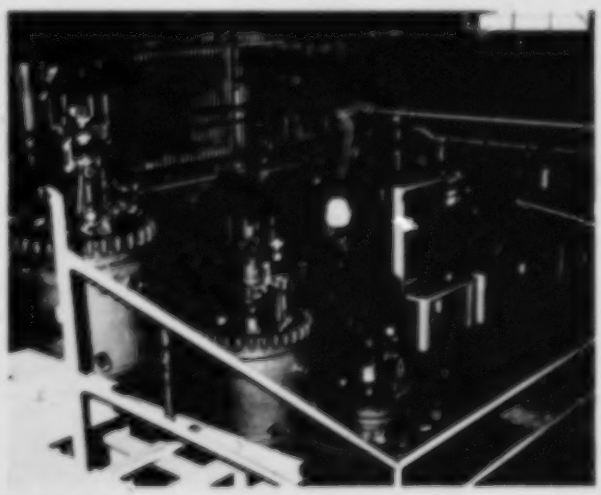


Fig. 3 (left). Comparison of methods for recovering alumina from bauxite or clay. Fig. 4 (right). Miniplant operated by the Bureau of Mines for determining the amenability of various nonbauxitic raw materials for alumina production. The research is being performed at the Bureau's Boulder City Metallurgy Research Laboratory under a cost-sharing cooperative agreement with ten private companies.

produce large quantities of mining wastes containing both alumina and unrecovered coal.

For more than 50 years the Bureau of Mines has been involved in research on methods of extracting alumina from domestic resources. As an important part of this work an extensive series of cost and technical evaluations was prepared of extraction processes developed both within and outside the Bureau. These studies showed that none of the proposed processes was competitive with the Bayer process. The alumina content of some of the resources being considered is shown in Fig. 2.

Three principal factors contributing to the higher cost of alumina from domestic resources are: (i) nonbauxitic sources contain less alumina (typically 25 to 30 percent Al_2O_3) than bauxite (about 50 percent Al_2O_3) and contain more gangue materials, (ii) processes for domestic resources are more complex and require high-cost materials of construction, and (iii) the processes for treating nonbauxitic materials require at least twice as much energy per ton of alumina as the Bayer process. Figure 3 shows block diagrams comparing the Bayer process with acid leaching of clay. Figure 4 shows the miniplant that was designed to treat approximately 70 pounds (1 pound = 0.45 kilogram) of raw material per hour from domestic resources, and to obtain data for designing a larger pilot plant for the most promising technique. In January 1974, invitations were issued to companies having U.S. smelting facilities to join the Bureau of Mines in a cooperative, cost-sharing effort. Ten companies have responded: Aluminum Company of America; Aluminum Company of Canada, Ltd.; Alumax, Inc.; Anaconda Aluminum; Combustion Engineering, Inc.; CONALCO, Inc.; Kaiser Aluminum and Chemical Corp.; Martin Marietta Aluminum, Inc.; Reynolds Metals Co.; and Vereinigte Aluminium-Werke AG. The Bureau of Mines also has bilateral agreement on this project with the Canadian Centre for Mineral and Energy Technology.

Nitric acid leaching of clay was the first process tested in the miniplant project. Calcined clay is leached with hot nitric acid, and the solution containing aluminum nitrate is separated from the solids, which are washed and discarded. Iron is removed from the solution by solvent extraction, and the purified solution is evaporated to crystallize aluminum nitrate nonahydrate. The latter is thermally decomposed to alumina and nitric acid for recycling. The thermal decomposition step is a major problem in this process because energy consumption is high and heat transfer is difficult.

The second miniplant, now under construction, will process clay with hydrochloric acid. The process is similar to the clay-nitric acid process, except that aluminum chloride hexahydrate is the salt crystallized. Because of the lower water of crystallization, energy consumption is reduced, but requirements for materials of construction are more difficult to meet than for nitric acid processing. An alternative to evaporation-crystallization is to precipitate the aluminum chloride hexahydrate by sparging the solution with hydrogen chloride gas. There are indications that this may reduce energy consumption even further.

Anorthosite is our largest single alumina resource, and its processing will be studied in the third miniplant to be built. Because of the large amounts of sodium and calcium oxides present, acid processing is not feasible, and lime-soda sinter or lime sinter methods must be used.

Sulfurous acid processing of clay will be the project of the fourth miniplant. Calcined clay is leached with sulfurous acid, and the solution is separated from the solids, which are washed and discarded. The aluminum sulfite solution is autoclaved under controlled conditions of temperature and pressure to precipitate a crude alumina, which is then purified by a modified Bayer process to cell-grade alumina. Sulfur dioxide liberated during autoclaving is recycled to the leach step.

Other potential sources of alumina include alunite, dawsonite, coal mining wastes, and coal fly and bottom ash. Vast quantities of these are available, and with increasing attention to coal as a source of energy they may become important as alumina resources in the near future.

Nickel and cobalt. The United States imports about 80 percent of its nickel needs. Value of imports exceeded exports in 1974 by nearly $400 million, and the deficit is projected to reach $1 billion by the year 2000.

The United States has about 7 billion tons of low-grade nickel-copper sulfide resources averaging about 0.2 percent nickel, principally as gabbro in the Duluth, Minnesota, area. Recently, new surface deposits of nickel laterites have been identified in southwest Oregon and northwest California, amounting to more than 400 million tons of ore containing about 0.7 percent nickel. Additional quantities are believed to exist at greater depths than those currently delineated. These new submarginal deposits could represent a major addition to the U.S. potential nickel supply. The Bureau of Mines is investigating new methods for treating both of these resources.

The Duluth, Minnesota, gabbro deposits contain cobalt in addition to copper and nickel, and to be economic a process must recover all three metals. A scheme now under study appears to have some promise. The ore is treated by flotation to recover a bulk sulfide concentrate of the copper, nickel, and cobalt. This concentrate is smelted to yield a matte which is leached in two stages with sulfuric acid. The first-stage leach, made at ambient pressure, selectively extracts the nickel and cobalt, leaving a residue containing the copper. The leach liquor is subsequently treated by solvent extraction and electrolysis to recover the nickel and cobalt, whereas the residue is leached at elevated temperature and pressure to obtain copper leach solution low in iron. The copper in this solution is then obtained by electrowinning. In tests to date, about 95 percent of the nickel and copper has been recovered from the matte by the two-stage procedure.

The lateritic material is not amenable to physical beneficiation and must be treated by a hydrometallurgy procedure. Such a procedure is being developed by the Bureau of Mines to selectively recover the nickel and cobalt. In laboratory evaluation of the process, the oxides in the laterite were selectively reduced with carbon monoxide at temperatures from 550° to 600°C. For material containing more than about 5 percent magnesia, pyrite addition or heat treatment after reduction was necessary to achieve satisfactory nickel and cobalt extraction for this range of reduction temperatures. Multistage leaching of the reduced material at ambient temperature and pressure in the presence of oxygen, ammonium sulfate, and ammonium hydroxide extracted up to about 90 and 85 percent of the contained nickel and cobalt, respectively.

The waste material from the laterites after removing nickel and cobalt contains a small percentage of chromium. Since the United States at the present time is completely dependent on imported chromium, the development of a satisfactory recovery process for the chromium in lateritic wastes would ensure at least a part of U.S. needs. At present, the Bureau of Mines is investigating the feasibility of recovering chromium from these lateritic wastes.

Extraction of titanium from abundant domestic ilmenite. The United States imports about 80 percent of its titanium needs and prices of rutile, the principal raw material used in the production of titanium tetrachloride, have risen sharply as demands have taxed the limited supplies available. The United States has only marginal and submarginal deposits of rutile, but has large deposits of ilmenite. Because of the high iron content of ilmenite, its application as a feed for titanium tetrachloride is not generally feasible, since iron

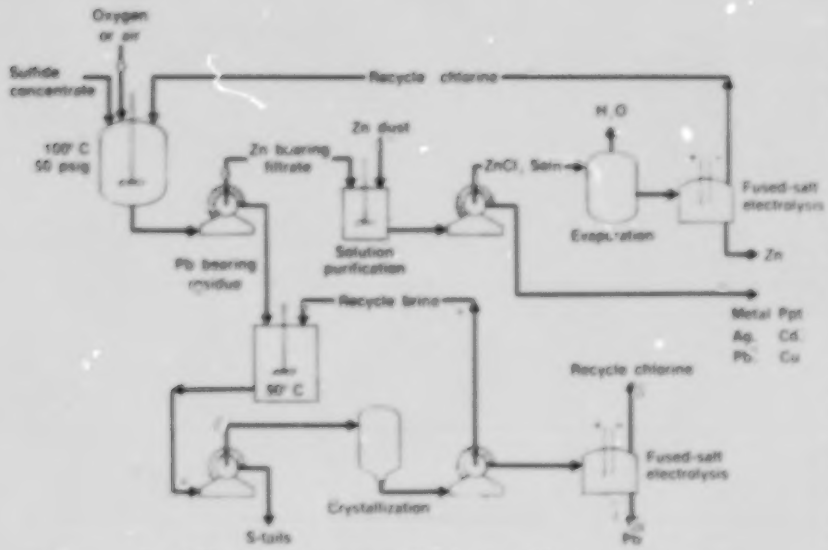


Fig. 5. Flowsheet for processing of lead-zinc sulfide concentrates.

consumes expensive chlorine which becomes a waste disposal problem. Ilmenite is used extensively as raw material in the sulfate process for preparing titanium dioxide pigment, but here disposal of the large amounts of waste ferrous sulfate has been an increasingly troublesome problem. As pigment production capacity must be increased, new plants are invariably chloride process plants (with titanium tetrachloride being used as feed) that in turn put additional demands on rutile imports.

For a number of years the Bureau of Mines has been conducting research on methods of producing rutile substitutes from abundant domestic ilmenite.

A process that has been developed involves direct chlorination of finely ground ilmenite in a fluidized coke bed. Titanium tetrachloride and ferric chloride are recovered separately by fractional condensation of the off gases from the chlorinator. The ferric chloride by-product of the reaction is then reacted with oxygen gas in a separate fluidized-bed dechlorinator to yield ferric oxide and chlorine, which may be recycled to the ilmenite chlorinator. The by-product ferric oxide may be pelleted and used as blast furnace feed. The results of this project have been of interest to the titanium industry. Consideration is now being given to a cooperative, cost-sharing, large-scale pilot plant to facilitate technology transfer to commercial practice.

A novel "mineral synthesis" technique is used in another process in which ilmenite is smelted with coke and lime to produce pig iron and a high-titania slag. The slag is treated with titanium pyrophosphate as a fluxing agent, under oxidizing conditions, and then quenched. Rutile crystals then separate from the slag and are recovered after a leaching step with dilute sulfuric acid. A synthetic rutile containing about 90 percent TiO_2 is the final product. A preliminary cost evaluation shows promising economics for the process.

In a third process a carbonate-flux smelting technique is used to treat ilmenite; 99 percent of the titania is recovered as slag and more than 95 percent of the iron is recovered as pig iron. The titania slag is then leached to produce a low-iron sodium titanate intermediate product that can be used as a feed for the sulfate process, yielding titania pigment. Use of this flux-smelting technique to provide the sodium titanate for manufacture of TiO_2 pigment eliminates the generation of large quantities of iron sulfate and the inherent problems relating to its disposal.

Lead and zinc. Lead and zinc smelters based on conventional pyrometallurgical technology cannot be built and operated economically on a small scale. Moreover, the increased costs of transporting ores and concentrates to a smelter limit production of lead and zinc from smaller mines. These factors have contributed to a decrease in U.S. overall production of lead and zinc. If full potential of our lead and zinc resources is to be realized, a more efficient process is needed capable of operating at small scale and at low cost.

The Bureau of Mines, therefore, is developing an aqueous chlorine leaching procedure combined with fused-salt electrolysis. The process is environmentally attractive and is effective in extracting nearly all of the metal values contained in sulfide concentrates (Fig. 5). Lead-zinc concentrates are chlorinated in aqueous slurry to produce lead chloride and elemental sulfur, and to solubilize metal values. After filtration, the residue is treated with hot brine to solubilize lead as the chloride. The lead chloride is crystallized from brine and dried. Lead and chlorine are recovered by electrolysis in a fused-salt bath; cadmium, silver, and copper are obtained from the leach liquor (which already contains zinc) by treatment with zinc dust, and the minerals are recovered by fire refining. The purified solution is evaporated to recover zinc chloride; the zinc and chlorine are then obtained by fused-salt electrolysis, and the chlorine is recycled.

Phosphate and fluorine. Resources of phosphate rock in the United States are estimated to be billions of tons. These resources could supply domestic demands for hundreds of years. However, if we consider only those resources which are exploitable by today's technology, production will decline sharply after 1985.

The most important phosphate resource in the United States is the Bone Valley Formation in Florida, where 100 million tons of ore are mined annually. This amounts to three-quarters of the domestic production and one-quarter of the world's production; however, large losses, of almost 40 percent, of phosphate minerals occur in the mining and processing of the ore. As yet this phosphate cannot be recovered economically with the technology available.

A promising long-term alternative is the direct digestion or acidulation of unbeneficiated Florida land-pebble matrix. Research thus far has shown that minus 20-mesh ore may be treated with sulfuric acid at 60°C in agitated, baffled vessels, with controlled throughput to allow the formation of large, easily filtered gypsum crystals. Phosphate recovery is 95 percent, compared with slightly more than 60 percent by present technology, and the residue is a sandy, easily filtered material that can be used to backfill mined areas. However, acid consumption is a little higher; the phosphoric acid product is only 30 percent P_2O_5 and will have to be concentrated; and the alumina content of the product is somewhat high—but these problems do not appear to be insurmountable.

In cooperation with the Florida State Bureau of Geology, the Bureau of Mines has been characterizing the phosphate-bearing Hawthorn Limestone Formation that underlies the phosphate land-pebble region of Florida. The formation is estimated to contain 2 to 4 billion tons of P_2O_5 at a concentration of 5 percent, which is lower than the average of 14.7 percent P_2O_5 being mined domestically. The Hawthorn Formation is not being mined because of the lack of a suitable beneficiation procedure. However, the Bureau of Mines has been able to obtain concentrates con-

taining up to 30.5 percent P_2O_5 with an attendant recovery of 81.5 percent of the phosphate by a fatty acid flotation process. These results indicate that this vast phosphate resource could be profitably utilized as raw material for phosphate fertilizer.

A companion problem is the recovery of fluorine values from the phosphate ore. The United States now imports 80 percent of the fluorspar it consumes annually, yet the fluorine content of the phosphatic rock mined is more than enough to satisfy our needs, if it can be recovered. Most is now scrubbed out as fluosilicic acid and is discarded, or remains as contaminant in the product phosphoric acid. Bureau work has shown how the waste fluosilicic acid may be converted simply to fluorspar. This involves (i) removing silica and other impurities by precipitation with ammonia, followed by filtration, and (ii) reacting the ammonium fluoride filtrate with lime to form fluorspar. Ammonia evolved is recycled back to the silica precipitation step. Alternatively, the fluosilicic acid may be converted to anhydrous hydrofluoric acid. Although this is somewhat more complicated than the conversion to fluorspar, yields are good and the product is of high purity.

Other work at the Bureau of Mines is focused on methods for more efficiently recovering the fluorine content of the phosphate rock. One approach which shows considerable promise is acidulation with recycle phosphoric acid, rather than sulfuric acid. The fluorine is mainly evolved in a single stream which may be easily recovered for further processing, as just described. Tests to date have shown that 95 to 98 percent of the P_2O_5 and more than 95 percent of the fluoride can be extracted by this method, and that 80 to 85 percent of the fluoride is evolved in the acidulation step. Current processes recover less than 50 percent of the fluoride in the rock.

Copper. The United States has large resources of copper, but the average grade of ore being mined is steadily declining as the more desirable deposits are worked out. Advances in technology are needed to make sure that our domestic resources can continue to be processed economically. Leaching of ore in place after fracturing is receiving increased attention. Because of the relatively high mining and beneficiation costs associated with working low-grade deposits, as well as the increasingly difficult problems of disposing of mining and milling wastes, the Bureau of Mines has been actively investigating in situ or solution mining techniques and is cooperating with industry to increase the efficiency of this technique for treating oxidized copper ores (*1*).

	SHORT TONS
MAJOR	
IRON	32,000,000*
LEAD	508,000
COPPER	483,000
ALUMINUM	285,000
ZINC	106,000
CHROMIUM	54,000
NICKEL	34,000
TIN	12,900
ANTIMONY	22,400
MAGNESIUM	4,500
MINOR	
MERCURY	342
TUNGSTEN	250
TANTALUM	190
COBALT	240
SELENIUM	15
PRECIOUS	
SILVER	1,993
GOLD	21
PLATINUM GROUP	12

*Includes Exports

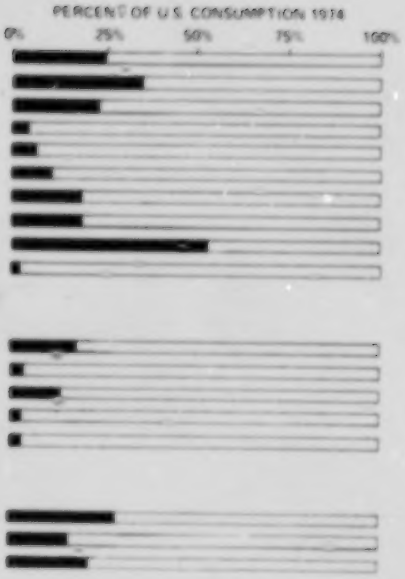


Fig. 6. Scrap metals recycled in the United States.

A significant development is the application of in situ leaching techniques at the Emerald Isle, Arizona, mine of El Paso Natural Gas Company. The company has been open-pit mining an oxide copper deposit and recently, in cooperation with the Bureau of Mines Salt Lake City Metallurgy Research Center and Twin Cities Mining Research Center, performed leaching tests on a 15,000-ton fractured ore sample at the floor of the pit. Copper has been recovered from the leach solutions by cementation.

Uranium. By 1990, the United States will be importing at least half of its uranium needs unless technology for recovering uranium at acceptable costs from low-grade domestic resources becomes available.

Because of the rapid depletion of our high-grade uranium deposits, future nuclear development will require the utilization of low-grade domestic resources containing less than 0.1 percent U_3O_8 or dependence on foreign supplies (*1*). For this reason, the Bureau's research is concentrating on new and improved processes for the recovery of uranium from low-grade and refractory sources.

Virtually all of the uranium being extracted from domestic sources comes from sandstones of New Mexico, Wyoming, and Utah. Until recently, uranium could be extracted from these ores by a simple dilute sulfuric acid leach at ambient temperature. Recovery of more than 95 percent of the uranium was common. Now, however, large mills are beginning to experience difficulty in dissolving this percentage of uranium from some of their ores because of interference from carbonaceous and sulfidic constituents. The Bureau of Mines is developing leaching procedures for treating these ores. The most successful procedure involves hot sulfuric acid leaching with the addition of nitric acid. Uranium extractions exceeding 90 percent have been attained from an ore by this method versus 25 percent for conventional leaching. In situ or solution mining techniques offer potential low capital and operating costs for treating these lower grade materials with a minimum of environmental problems. In situ leaching with sodium carbonate has been applied to an unconsolidated uraniferous ore body and leaching is being considered for sandstone using acid leaching. This technology is in its infancy, and at this time much more fundamental and engineering data must be developed before in situ leaching is broadly applied to uranium resources.

Minimizing Mineral and Metal Needs

The increasing demand for materials of construction is a serious drain on the limited U.S. supply of minerals. A major portion of this demand originates from a need to produce replacement materials. For example, a substantial portion of the steel capacity in the United States is being used to replace corroded and rusted steels already in use. Nickel, cobalt, and other critical materials are used in high-temperature alloys that have short service lives. While longer lasting materials are needed for applications at both low and high temperatures, the alternative approach of devel-

oping domestically available substitutes or interchangeable materials would have a greater impact on reducing demand for critical materials and provide some insurance against shortages.

Minimization of mineral and metal needs by development of high-quality and improved-performance materials from abundant domestic resources, such as iron and molybdenum, will lead to subsequent reduction in the demand for scarce or imported materials in short supply. Among the several facets of the research at the Bureau of Mines on this objective are fundamental studies to determine the oxidation kinetics and the corrosion mechanisms of iron and iron-chromium alloys in order to provide the base from which better materials can be made and from which interchangeable substitutes can be developed. The corrosion problem alone is responsible for annual replacement of materials worth more than $20 billion, most of it attributed to iron-base alloys.

The Bureau is using a unique approach in its study aimed at understanding the mechanisms of corrosion and passivation with respect to iron and iron-chromium alloys. This approach utilizes a linear ion accelerator in conjunction with advanced physical techniques, such as Auger electron spectroscopy. The techniques are being used to study the formation of ultrathin oxide and sulfide films on iron-chromium alloys at temperatures from 24° to 300°C and in atmospheres of O_2, SO_2, and CO_2. Studies have been carried out during the initial stages of metallic oxidation and corrosion. In addition, measurements have been made of the diffusion rates of carbon, sulfur, and other impurities from the bulk of the metal to the surface where impurities can affect corrosion reactions.

Also, a new technique for preparing sample alloys is being developed. With the linear ion accelerator, alloying additions to pure metal samples are being implanted in precise quantities and well-defined geometries in the crystal lattices at metal surfaces. This technique makes it possible to evaluate metallic corrosion in a new and precise manner, and adds a new dimension to corrosion research. It also may herald a new method for producing bimetallic materials.

In order to provide alloys for use at high temperature, research workers at the Bureau of Mines have turned their attention to iron, the only inexpensive alloy base that might fulfill the high-temperature requirements. Several techniques with potential for producing the essential properties are being examined. Emphasis is placed on incorporating ultrafine, refractory oxide particles in iron to strengthen it. Powder metallurgy techniques are utilized. The research has centered on ultrafine refractory oxide dispersoids because they retain the strength of metals to high temperature better than other types of strengthening mechanisms. Of the iron-strengthening techniques studied, internal oxidation, oxy-reaction, and powder blending methods produced the strongest alloys. These conclusions are based on stress-rupture tests at 800°C, the present target.

Secondary Resource Recovery

Metallurgical recycling as a partial solution to materials shortages. The gap between our minerals and metals requirements and the remaining easily accessible world supplies is widening. As the nation's needs continue to grow and as per capita consumption of materials in other countries increases at an even faster rate than ours, it is becoming increasingly difficult for the United States to fill its ever-growing minerals deficit by primary domestic production and imports, even at increasing prices. A partial solution to this vexing problem is to increase our capability for recycling of minerals and metals contained in waste materials. Figure 6 illustrates the opportunities for increasing the recycling of scrap metals in the United States.

Bureau research is directed toward development of methods to recover the valuable mineral constituents in metallurgical wastes, and to improving the recovery and quality of the secondary resources being recycled. Widespread application of the results of this research should increase the portion of U.S. metal needs met by scrap. For example, the iron discarded in urban refuse is one of our most important low-grade metal and mineral resources, our only growing and renewable mineral resource.

Stainless steel flue dusts. For many years the Bureau of Mines has been concerned with the refining of secondary metals such as lead, zinc, copper, and brass. More recently, attention has been focused on recovering metals and minerals from a variety of unused or underused wastes to encourage more complete recycling.

An estimated 10 million pounds of chromium, 2.5 million pounds of nickel, and 250,000 pounds of molybdenum are lost each year in the wastes generated in the production of stainless steel. About 40 percent of this lost material is found in the flue dusts; the remainder occurs as mill scale and grinding swarf.

A treatment procedure has been developed for recovering over 90 percent of the metals from these wastes in an alloy containing 60 to 67 percent iron, 3 to 9 percent nickel, 9 to 17 percent chromium, and 0.25 to 4 percent molybdenum. This alloy can be recycled to the stainless steel furnaces.

The method consists of converting a mixture of flue dust, mill scale, grinding swarf, and coke breeze to pellets; a small quantity of Portland cement is used as a binder, and the pellets are reduced by preliminary heating in a furnace, followed by secondary reduction with ferrosilicon for more complete recovery of chromium. The process is versatile enough to accommodate a variety of charge ingredients with no adverse effect on the process. Zinc and lead, which are found in the flue dust, also are recovered as by-products in the form of oxide fume containing up to 40 percent zinc and 20 percent lead.

Aluminum dross. Another phase of metallurgical recycling is concerned with the waste dross and slag associated with primary production of aluminum. Large tonnages of aluminum-containing dross are generated annually by the aluminum industry, part of which is recovered in the secondary aluminum industry by a process in which large quantities of salt slag also are produced. The slag, containing fluxing salts, aluminum metal, and aluminum oxide, is currently disposed of by dumping. As a result, valuable metal and oxide are lost and the salts composing the flux can lead to pollution problems.

To reclaim the valuable slag constituents and eliminate the pollution problems, the Bureau of Mines had developed a hydrometallurgical process to recover the salt flux and most of the aluminum metal for recycling to the aluminum dross treatment furnace. The reclaimed aluminum oxide also has use as a constituent in preparing hot-top compounds and as a source of alumina for the cement industry.

Also, a method is being developed by the Bureau of Mines to recover metallic aluminum from dross without the objectionable salt slag being formed. In this method an inert atmosphere is used instead of a salt flux to protect the aluminum metal from oxidation. Recovery of 80 to 100 percent of the aluminum metal contained in primary dross is effected by simply heating and stirring the dross in the inert atmosphere.

Metal recovery from waste industrial solutions. Waste solutions from industrial electroplating, etching, and pickling operations contain thousands of tons of valuable metals. In many cases the metal content of the waste solutions is greater than that of the primary ores now being processed. The lack of technology for treating plating wastes to recover metal values has encouraged the disposal of spent solutions to sewers and streams. Significant tonnages of

the valuable metals can now be recovered with the Bureau's "waste-plus-waste" process, which can be successfully used to economically treat the major types of acid and alkaline plating wastes containing cadmium, chromium, copper, nickel, and zinc, and to treat both concentrated and dilute wastes. The process consists of the addition of an acid waste to an alkaline waste, in suitable proportions, so that at the optimum *p*H values of the mixtures, metals are virtually quantitatively precipitated. In the five waste-plus-waste combinations investigated, successful recovery of the metals always resulted. Also, the filtrate from the processing was relatively harmless compared with the original wastes and meets most water quality standards.

In summary, during the last three decades the United States has been a net importer of minerals, and the forecast for the future behooves us to implement a strategy of technologic insurance against shortages in minerals and metals by making real innovations and taking major steps forward in minerals processing and allied fields. To meet the challenge of processing lower grade domestic resources, the Bureau of Mines is conducting an integrated program for advancing minerals technology, minimizing mineral and metal needs, and improving the recovery of secondary resources for recycle. Although the program is designed primarily to meet long-term national needs, it is also concerned with current problems of broad scope that affect the nation's immediate mineral position.

References

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Minerals Extraction and Processing: New Developments

Examples of new industrial practice illustrate advances in minerals technology.

Joe B. Rosenbaum

Supplies of raw materials can often be extended by improving the ways of extracting and processing ores. Thus, ores once considered uneconomical may become accessible. Changing economic and legal conditions may require extensions of existing technology or altogether new techniques. Innovation in industrial extraction and processing of metals has in fact been accelerated in the last few years by new environmental constraints and by disruptions in energy supply and costs.

Interest in continuous copper smelting has been largely motivated by the need to reduce sulfur dioxide emissions without incurring excessive costs or facing the closing of plants. The replacement of mercury in gold recovery by a recently improved activated carbon process was similarly motivated by the necessity for pollution control. New recovery processes for nonmagnetic iron ore (of which the United States has huge resources) and for uranium, on the other hand, have opened up hitherto uneconomic deposits and thus extended the resource base. These four examples of newly adopted processes indicate how the technology base is being broadened, although they do not necessarily reflect industry trends.

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Continuous Copper Smelting

The control of pollutants in gaseous emission from reverberatory furnaces that smelt copper concentrate to matte (*1*) has long been a troublesome area in smelter operations. This is because the burning of a large amount of fuel with air inside the furnace yields a vast volume of combustion gas lightly flavored with SO_2, from a few tenths to 1 percent. Because costs of cleaning up the gas are generally proportional to the gas volume treated, reverberatory gas-cleanup costs are disproportionately high relative to its SO_2 burden. Combustion with oxygen or air-oxygen mixtures, and prior heating of the combustion air with or without oxygen enrichment, are ways in which the gas volume can be sharply reduced.

A reduction of tenfold or more in the offgas volume is offered by the flash smelting processes introduced about 25 years ago. The International Nickel Co. (INCO), at Sudbury, Canada, injects dried copper concentrate entrained in oxygen (95 percent grade) through lances into opposite ends of a rectangular furnace (*2*). Reaction heat from partial oxidation of sulfides is sufficient to sustain the smelting operation. Gas at a temperature of 1260°C (2300°F) containing 70 to 80 percent SO_2 leaves the furnace through a center uptake. The gas is cooled, cleaned, and processed for daily recovery of 300 tons (1 short ton = 0.9 metric ton) of liquid SO_2, which is marketed. Slag containing 0.6 percent copper is discarded, and matte containing 45 percent copper is blown to blister copper (*3*) in conventional converters.

Outokumpu at Harjavalta, Finland, initially used air heated to 500°C (930°F) for injecting dried concentrate and fuel oil into a vertical cylindrical chamber at one end of a rectangular furnace with the gas uptake at the other end (*4*). The offgas contained 12 percent SO_2. Subsequently, the air was enriched to contain 35 percent O_2 and the preliminary heating was reduced to 200°C (390°F). This permitted substantially autogenous smelting. The capacity was increased about 60 percent, and the offgas grade was increased to 18 percent SO_2. Slag from the furnace contains too much copper to be discarded and must be treated again. Matte contains 40 to 50 percent copper, depending on concentrate analysis and degree of oxygen enrichment. Some 18 Outokumpu-engineered flash furnaces are now operating or are under construction in ten countries. An Outokumpu-type flash furnace built by Phelps Dodge at Hidalgo,

New Mexico, started operation at the end of 1975. The SO_2 in the flash-furnace offgas is to be reduced with a hydrocarbon in a high-temperature catalytic system to make 400 tons of elemental sulfur per day (*5*).

Electric resistance heating in lieu of burning fossil fuels is another way in which the gas volume in matte smelting can be drastically decreased. Elkem Spigerverket of Norway pioneered the technology, which uses three, four, or six self-baking carbon electrodes for heating the slag (*6*). Offgas temperature is only 700°C (1300°F), and the SO_2 concentration is about 5 percent. The slag contains about 0.5 percent copper and is discarded. Matte grades range from 40 to 50 percent copper. About six matte-smelting electric furnaces are in operation or are being built. The Tennessee Copper Co. at Ducktown, Tennessee, and the Inspiration Copper Co. at Inspiration, Arizona (*7*), have electric furnaces in operation, with respective capacities of 20,000 and 150,000 tons of copper per year. An electric furnace designed to smelt 120,000 to 150,000 tons of copper per year was started up in December 1975 by Anaconda at Anaconda, Montana.

Copper matte, whether made in reverberatory, flash, or electric furnaces, is blown with air, or sometimes with oxygen-enriched air, to slag off iron and eliminate sulfur as SO_2 (*8*). Converter slags are high in copper and are re-treated by recycling to the matte-smelting furnace or by slow cooling and flotation to make a copper concentrate for recycling to the matte-smelting furnace. Blister copper from the converter is further fire-refined to make a marketable product or is cast into anodes for electrorefining. The converter offgas is another potential source of significant air pollution. Converting is a batch, stagewise process, with wide variations in the SO_2 grade of the offgas. A large smelter in which several converters are used can schedule operations to obtain converter gas containing at least 4 percent SO_2, which is suitable for conversion to sulfuric acid.

Converting matte to blister is an exothermic operation. Smelting concentrate to matte, unless combined with partial converting, is an endothermic operation. To improve fuel efficiency, eliminate or minimize slag recycling, and obtain a uniform flow of rich SO_2 gas, much attention has been given to developing processes for continuous smelting and converting in a single furnace or in contiguous furnaces.

One of the early proponents of continuous smelting was Howard Worner of Conzinc Rio Tinto in Australia, the developer of the Worcra process (*9*). Copper concentrate and flux are injected with air through lances into the end of a U-shaped furnace or into the center of a rectangular furnace. Slag flows to one end of the furnace where entrained matte drops out and returns to the melting zone. Slag containing about 0.5 percent copper is discarded. Matte flows to the other end of the furnace where it is continuously converted to blister by top-blowing with air and flux through lances. Slag formed in the converting zone returns to the melting zone. Blister copper containing up to 1 percent sulfur collects in a well for continuous discharge. Furnace offgas contains about 10 percent SO_2. A semicommercial Worcra furnace at Port Kembla, Australia, smelted a nominal 70 tons of concentrate per day—6000 tons of copper per year—in operating campaigns of up to 9-month duration from 1968 to 1970.

Noranda Mines, Ltd., Noranda, Canada, began experimenting with continuous copper smelting in 1964 (*10*). In Noranda's commercial process, operated since 1973, concentrate and flux are formed into pellets and thrown by a slinger belt into one end of a horizontal, cylindrical furnace. A fuel-fired burner extending through the same end melts the feed. Matte that forms is continuously blown to a crude blister, consisting of about 98 percent copper, by air injected through submerged tuyeres. Slag flows the length of the furnace (67 feet) (1 foot = 0.3 meter) before discharging over a weir. A burner firing through the end wall keeps the slag fluid for discharge. The slag, containing about 12 percent copper, is cooled slowly in pits for several days, then crushed, ground, and floated to recover a concentrate—which contains, by analysis, 50 percent copper—for recycling to the Noranda furnace. The flotation tail contains 0.5 percent copper and is discarded. Furnace offgas at a temperature of 1315°C (2400°F) contains about 4 percent SO_2. The furnace at Noranda is rated at 800 tons of concentrate per day—equivalent to 200 tons of copper per day. Because periodic shutdowns are necessary for repairs to the furnace lining, the capacity is about 50,000 tons of copper per year. The remainder of the Noranda smelter capacity of about 200,000 tons of copper per year is provided by conventional reverberatory furnaces and converters.

Owing partly to the interest of Kennecott Copper Co. in using Noranda-type furnaces in its Garfield, Utah, smelter, tests were made at Noranda with oxygen-enriched air. When the burner air was enriched to contain 50 percent O_2 and the tuyere air to contain 35 percent O_2, the furnace capacity doubled and the SO_2 content of the offgas increased to 13 percent. The amount of liquid oxygen used was 422 tons per day. Kennecott has ordered three Noranda-type furnaces. The first is scheduled for operation in 1977. The furnaces in Utah will be operated to produce a matte having 75 to 80 percent copper which will be blown to blister in converters. This is necessary because certain impurities in the Kennecott concentrate, such as bismuth, are best removed by fuming or slagging in a converter.

The second continuous copper smelting system to attain commercial scale is Mitsubishi's, installed at its Naoshima, Japan, smelter in 1974 to produce 50,000 tons of copper per year. A description of the semicommercial operation with a capacity of 18,000 tons of copper per year, which came on-stream in 1971, has been published (*11*). Concentrate and flux were injected through lances with air enriched to 25 percent O_2 into the first of three contiguous stationary hearth furnaces. Both matte and slag flowed from the smelting furnace into an electric furnace settler where pyrite and coke were added to facilitate sedimentation of matte droplets from the slag. From the settler, slag containing 0.5 percent copper was discarded, and matte containing about 50 percent copper flowed to the converting furnace. By top-blowing air and flux through lances, the matte was converted to blister of 98 to 99 percent copper grade, and a slag containing 7 to 15 percent copper was made for recycling to the smelting furnace. Combined offgas from the three furnaces contained 10 percent SO_2. Mitsubishi has a copper-smelting capacity of 150,000 tons per year in conventional reverberatory furnaces and converters in addition to the 50,000-ton annual capacity of the three-furnace system. In April 1975, Texasgulf, Inc., announced it would build a Mitsubishi three-furnace smelter at Timmins, Ontario, Canada, to make 130,000 tons of copper per year (*12*). The Timmins smelter is scheduled to start operation in 1978.

Why has there been commercial adoption of Noranda and Mitsubishi processes and not Worcra, which appears to do the whole smelting job in one furnace and does not require handling slag for recycling outside the furnace? The answer may be that Conzinc Rio Tinto does not operate a copper smelter, whereas both Noranda and Mitsubishi operated large copper smelters and were able to experiment with a part of the capacity.

The demonstration of hydrometallurgical alternatives to smelting of copper concentrate (*13*) was aborted when the Anaconda "Arbiter" process plant at Anaconda, Montana, which is rated at 36,000 tons of copper per year, was placed on standby in June 1975. Both the "Arbiter" plant at Anaconda and the Cyprus Mines "Cymet" demonstration plant at Green

Valley, Arizona, started up in the fall of 1974. In announcing the closing of the Arbiter plant, Anaconda said that the plant performed satisfactorily, but that the capacity was in excess of its needs. The Arbiter process leaches copper concentrate in ammoniacal solution at 70°C under about one-third of an atmosphere (several pounds per square inch) of oxygen pressure. Copper is recovered from solution by solvent extraction and electrolysis (*14*). The Cymet plant, designed to produce 1500 to 3000 tons of copper per year, is believed to be in pilot-plant status to work out process modifications because of operating problems in the demonstration unit. Duval's "Clear" process plant at Esperanza, Arizona, slated to produce 32,500 tons of copper per year, is still under construction. Both Cymet and Clear use chloride-leach systems and recover copper powder by reduction of cuprous chloride with a reducing gas or by electrolysis of cuprous chloride solution.

The Hecla–El Paso combination hydromet-pyromet plant at Lakeshore, Arizona, started up in October 1975, and is expected to produce 65,000 tons of copper per year by interlocked flowsheets that separately process oxide and sulfide ores (*15*). About 30,000 tons of copper per year are to be made by electrowinning after the sulfide concentrate has been roasted and leached, and 35,000 tons of copper are to be precipitated from the oxide circuit leach liquor by cementation on iron. The iron for cementation, plus accessory precious metals, is to be recovered by reduction of the silicious iron residue that remains after the sulfide concentrate is roasted and leached. Cement copper containing about 64 percent copper is to be further treated by smelting, or by leaching and electrowinning.

Improved Activated Carbon Systems for Gold

Many of the troublesome and expensive liquid-solid separations in processing minerals have been greatly ameliorated by the development of polymeric flocculants (*16*). Such effective aids for thickening and filtration were unknown in the 1930's when T. G. Chapman at the University of Arizona developed his carbon-in-pulp system for gold cyanidation (*17*). In Chapman's original system, the dissolved gold was adsorbed by finely ground activated charcoal; the charcoal subsequently was separated from the pulp by flotation. Gold was recovered from the carbon concentrate by burning or smelting. In an alternative system, Chapman and his co-workers used particles of activated carbon coarser than the ground ore as the gold adsorbent. The carbon was enclosed in a cylindrical screen that rotated in the leach pulp. A concentrated gold solution was obtained by stripping the gold-loaded carbon with hot cyanide solution (*18*). John Zadra and coworkers of the U.S. Bureau of Mines further modified the system by adding an electrolytic cell for continuous removal of gold from the hot strip liquor (*19*). A commercial carbon-in-pulp plant was operated by the Golden Cycle Corp. at Cripple Creek, Colorado, from 1954 to 1960. Coarse carbon was loaded with gold by mixing and screening in a countercurrent system, and the carbon, loaded to about 40 ounces (1 troy ounce = 31.1 grams) of gold per ton, was stripped and recycled by the Zadra method (*20*).

In December 1970, the Homestake Mining Co. was enjoined by federal decree from using mercury in its milling plant at Lead, South Dakota, because of downstream pollution. When mercury was used to collect gold in the grinding circuit, about 60 percent of the gold was recovered by amalgamation, and an additional 35 percent was recovered by separately leaching the sand and slime fractions in cyanide solution. The slimes-treatment plant contained 30 huge filter presses in which the slimes were sequentially leached and washed. Upon removing mercury from the plant circuit, gold recovery, especially from the slime circuit, dropped precipitously. Homestake's difficulties provided an opportunity for the Bureau of Mines to test its own new concepts for improved gold extraction, gold loading, and carbon handling in a cyanide carbon-in-pulp system (*21*). The new system optimized the separate leaching, loading, stripping, and carbon regeneration operations. Its performance was demonstrated at Homestake in a miniplant that handled 2 tons of slimes per day. By extrapolation of the design from the miniplant, Homestake was able to start up its commercial carbon-in-pulp plant, treating 2000 tons of slimes per day in April 1973 (*22*). Full-scale operation with predicted gold recovery and operating costs was attained in August 1973. The carbon leaving the Homestake four-stage countercurrent mix-and-screen circuit contains between 300 and 400 ounces of gold per ton. Stripped and regenerated carbon for recycling contains 5 ounces of gold per ton.

In another application of Bureau of Mines technology for gold recovery, Cortez Gold Mines at Cortez, Nevada, is heap-leaching low-grade ore with cyanide solution, then loading the gold on activated carbon in a countercurrent expanded-bed system (*23*). The loaded carbon is rapidly stripped with a dilute solution of sodium hydroxide at 3 atmospheres (75 pounds per square inch) and 121°C (250°F), and the strip liquor is electrolyzed for gold recovery. Procedures generally analogous to those used at Cortez are planned for the Smokey Valley Mining Co. operation now being built near Tonopah, Nevada, for heap-leaching about 8000 tons of low-grade gold ore per day.

Flocculation-Flotation of Iron Ore

The Lake Superior iron ore district contains 20 billion long tons or more (1 long ton = 1.016 metric tons) of nonmagnetic iron ore that requires beneficiation to make a marketable concentrate. Only a trickle of concentrate has been made from the nonmagnetic ores compared with production from magnetic ores that now yield about 40 million long tons of iron oxide pellets per year (*24*). The nonmagnetic ores contain hematite and goethite as the main iron minerals and, like the magnetite-bearing taconites, require extremely fine grinding for liberation of iron minerals from the associated gangue. Problems inherent in beneficiating the nonmagnetic ores owing to the intimate and complex association of various and varying iron and gangue minerals were identified by the Bureau of Mines (*25*). Potentially feasible beneficiation methods appeared limited to reductive roasting-magnetic separation and flotation (*26*). The magnetic-roasting route appeared to be more capital- and energy-intensive and more expensive than flotation.

Among the iron ore flotation methods described by Clemmer in the 1940's were anionic (fatty acid) flotation of iron oxide, depression of iron oxides and anionic flotation of activated silicious gangue, and depression of iron oxides and cationic (amine) flotation of silicious gangue (*27*). All three methods usually required thorough desliming of the ground ore at about 20 micrometers to assure subsequent selectivity in flotation and to avoid excessive reagent consumption. The slime fraction was discarded. For ores containing iron oxides of earthy texture, desliming often resulted in excessive loss of iron oxides. Commercial flotation of nonmagnetic ores was initiated at the Humbolt mill of the Cleveland Cliffs Iron Co. on the Marquette Range in Michigan in 1955. This was followed by a second Cleveland Cliffs operation, the Republic Mill, in 1956, and by Hanna Mining Co.'s mill at Groveland, Michigan, in 1959. The last two mills are still operating. All three mills floated hematite with a fatty acid reagent from a deslimed pulp (*24, 28*). Other Lake Superior iron ores responded less favorably to the hematite flotation procedure.

In searching for a flotation technique that would be widely applicable to diverse iron ore types, Frommer and co-workers of the U.S. Bureau of Mines observed and capitalized on the selective flocculation of iron oxides that occurred when starch was added to a dispersed ore pulp (*29*). When the iron minerals were properly flocculated, silicious fines could be discarded by desliming with minimum loss of iron oxides. Nonslime silicious particles then could be selectively floated with either anionic or cationic reagents and discarded. The product of the flotation operation was high-grade iron oxide concentrate. The technique was refined in cooperative studies by the Bureau of Mines and the Cleveland Cliffs Iron Co. starting in 1961, and then developed for commercial production from Cleveland Cliffs' Tilden, Michigan, ore body (*24, 30*).

The Tilden plant began operation in October 1974 and attained its design production rate of 4 million long tons of pellets annually from 10.5 million long tons of 36 percent iron ore at the end of 1975. Cost of mine development and mill construction exceeded $200 million. As an aid to blending the ore for uniform mill feed, relatively small (75-ton capacity) trucks are used for hauling the ore from the open-pit mine. A gyratory crusher breaks the ore to 10-inch (1 inch = 2.54 centimeters) size.

Primary grinding is done in six autogenous mills, 27 feet in diameter by 14.5 feet long, each driven by two motors capable of a combined output of 5720 horsepower. Caustic soda and sodium silicate are fed to the primary mills for thorough dispersion of the ore slurry. Secondary grinding is done in 12 pebble mills, 15.5 feet in diameter by 30 feet long, in closed circuit with cyclone sizers. Pebbles for fine grinding are minus 3-inch, plus 5/8-inch ore that are screened from the primary mill circulating load. Solids in the cyclone overflow are 75 to 80 percent minus 500 mesh (33 micrometers). The ground ore slurry has a *p*H of about 11 and a density of about 11 percent solids.

To flocculate the iron oxides, a 2.5 percent solution of corn starch is added to the slurry of finely ground ore, which then flows to 12 thickeners 55 feet in diameter for desliming. Slimes in the thickener overflow (at about 2 percent solids) contain 10 to 13 percent iron and are discarded; water is reclaimed for further use. Thickener underflow (50 percent solids) is conditioned with more starch to ensure iron flocculation and depression, and then floated in six banks of cells. Each bank contains 25 cells; individual cells have a capacity of 500 cubic feet. Silica is floated by the addition of an amine reagent to the flotation cells and discarded. Cationic flotation was selected over the anionic method because of better stability as the hardness of the process water changed. The amine used is a primary amine containing 16 to 18 carbon atoms and is prepared from tallow fatty acids. It is 30 percent neutralized with acetic acid, and fed as a 5 percent dispersion in water. The concentrate, containing about 65 percent iron, is thickened and then filtered while hot to obtain a filter cake containing 10.5 percent moisture for balling; bentonite is added as binder. The green balls are first heated on a grate, then indurated in a rotary kiln 25 feet in diameter by 160 feet long. About 11,000 tons of finished pellets containing 66 percent iron are produced daily by milling 30,000 tons of 36 percent ore per day. Distribution of iron in the feed is 7 percent in the slime thickener overflow, 23 percent in the floated silica, and 70 percent in the pellets. Two expansion stages of the Tilden operation are contemplated, with timing dependent on economic conditions. Each expansion would add 4 million tons of pellet capacity annually.

In situ Leaching of Uranium

Uranium deposits too deep and too low in grade for economical uranium recovery by surface or underground mining and conventional milling are known in southern Texas. These loosely consolidated, uranium-bearing sandstones, occurring at depths of about 300 to 700 feet, have long been an attractive target for in-place leaching proposals and experiments. The development of a successful technique promised low capital and operating costs, minimum land-surface disruption, and avoidance of disposal or storage of mill tailings.

Among the established alternatives to surface or underground workings for extracting minerals are the solution mining of salt (*31*) and potash (*32*), the mining of sulfur by the Frasch process (*33*), and underground leaching of copper (*34*) and uranium (*35*) from caved ore and wall rock. The underground leaching usually has been performed in conjunction with, or as the terminal phase of, underground mining.

There was little in any of these techniques directly transferrable to the in-place leaching of the Texas uranium ores. However, uranium-recovery practice from mine water in the Grants, New Mexico, district does suggest a clue. In the Grants district about 5000 gallons (1 gallon = 3.8 liters) per minute of barely alkaline mine water containing 10 parts per million (ppm) of U_3O_8 is treated by resin ion exchange for recovery of 100 tons per year of U_3O_8. Part of the depleted solution from ion exchange is recycled to worked-out areas of the mines. The clue to in-place leaching of the Texas uranium deposits without excessive reagent use and without plugging the ore formation appears in the use of extremely dilute alkaline leach solution with a low uranium-loading and a high circulation rate.

In April 1975, a commercial in-place leaching operation was started by Atlantic Richfield Co. (Arco) and partners near George West, Texas, for the planned production of 125 tons per year of U_3O_8 (*36*). The leach solution for this project is believed to be a dilute solution of sodium or ammonium carbonate and bicarbonate. It is circulated through the ore strata at a rate of 2000 gallons per minute through an initial pattern of 66 injection wells and 46 extraction wells over an area of 3 acres (1 acre = 0.4 hectare). Maximum distance between an injection and extraction well is about 35 feet. Oxidation is necessary for satisfactory dissolution of the uraninite ore mineral. This probably is effected by sparging oxygen into the strata or by adding hydrogen peroxide to the leach solution. Leach liquor from the extraction wells is clarified by passage through a column of activated carbon. Uranium is recovered from the clarified solution by conventional anion resin exchange in columns, and the depleted solution is recycled to the injection wells. Groundwaters in the leach area were characterized before leaching started, and a ring of monitor wells was established to warn of escaping leach solution. To assure a hydraulic gradient toward the extraction wells, more solution must be pumped than is injected.

Wyoming Minerals Co., a subsidiary of Westinghouse, plans to have its in-place leaching operation in production near Bruni, Texas, early in 1976. The Wyoming Minerals operation, also rated at 125 tons of U_3O_8 annually, is believed to be generally similar to Arco's. Also Union Carbide Corp. has scheduled uranium production by in-place leaching at its Palangana Dome property in Duval County, Texas, starting in 1976. The Mobil Oil Corp. has a uranium in-place leaching test program under way in Webb County, Texas.

To yield the planned production of 125 tons of U_3O_8 per year, Arco's 2000 gallons per minute of leach solution would have to contain about 30 ppm of U_3O_8. This is only 1/20 or less of the uranium content in leach solution processed by conventional mine-mill operations. However, dilute alkaline solutions are notably amenable to ion-exchange processing, compared with highly contaminated acid leach solutions. Compared with the production of 125 tons of U_3O_8 annually by the in-

place leaching operations, the 19 U.S. uranium mills in operation, on standby, or under construction have capacities of 200 to 4000 tons of U_3O_8 per year. For meeting the uranium requirements of nuclear power generation, 125 tons of U_3O_8 is roughly equivalent to the annual requirement of a 500-megawatt reactor.

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Manganese Nodules: A Mineral Resource on the Deep Seabed

Allen L. Hammond

Fishing and offshore oil drilling are still the most significant of man's efforts to tap the resources of the 70 percent of the earth covered by oceans, although minerals such as salt, tin, and limestone are extracted from the sea or dredged from the continental shelf in growing quantities. The most glamorous and perhaps the most mysterious marine resource, however, is the billions of tons of metals contained in manganese nodules that lie scattered over the seabed in the once inaccessible depths of the open ocean.

The nodules contain iron, nickel, copper, cobalt (and traces of two dozen other metals) in addition to manganese, often in concentrations comparable to those in land ores. This wealth of metals and the prospect of deep sea mining operations to recover them have stirred up interest among oceanographers and industrialists alike. Indeed, to judge from newspaper stories about the inexhaustible riches of the deep sea floor and from the intensity of the international debate over the ownership of these resources, a new gold rush might be beginning. But despite investments estimated at $100 million in the development of mining and processing technology, the economic viability of exploiting the nodules is still uncertain. Nor is the resource unlimited. Although nodules occur on the seabed in many parts of the world, they are unevenly distributed. Only a few areas have nodules with a high metallic content in sufficient abundance to make mining feasible. Efforts to explain this distribution pattern and to account for the formation of the nodules are leading, however, to a better understanding of deep ocean geochemistry. Among the more intriguing results is recent evidence that manganese nodules, much like coral reefs, are habitats for a variety of life forms (protozoans and other microorganisms) and seem to grow in part through biological action.

Manganese deposits on the sea floor occur as thick slabs or crusts, as thin coatings on basalt rocks, and as nodules, some of which were recovered as early as the 1872 expedition of the *Challenger*. Nodules, the commercially significant type of deposit, are black or brown agglomerations of manganese oxide and iron oxide minerals. The nodules range in size from about 1 to 15 cm across. They are extremely porous, and differ widely in shape, internal structure, and composition from one deposit to another—even within the space of a few hundred meters. Nodules are found predominantly in areas of oxygen-rich waters and low sedimentation.

The nodule beds most favorable for mining appear to lie in the Pacific Ocean, southwest of Hawaii and just north of the equatorial zone of high biological productivity, according to D. R. Horn and B. M. Horn of Lamont-Doherty Geological Observatory. The richest deposits occur in a narrow band, perhaps 200 km across and 1500 km long, running roughly east-west around 9° latitude (*1*). Not only are the nodules in this band high in copper and nickel content, but they are also very abundant. The seabed in this area is about 5000 m deep and the sediments include silicon-rich remains of plankton (Radiolaria). High concentrations of nodules are also found along the southern edge of the equatorial belt, but the deposits, like those of the Atlantic and Indian oceans, are relatively poor in copper and nickel.

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(Deposits high in cobalt, however, have been discovered in the South Pacific.) As a result, both scientific and commercial interest have been focused on the North Pacific beds.

The structure of nodules from different regions varies widely, but most appear to be layered, often in the form of concentric rings around a small nucleus (*2*). According to R. K. Sorem of Washington State University, the layers represent compositional and mineralogical boundaries and range in size from rings visible with the eye down to microscopic structures. The layers as they are originally laid down on the nodule surface are honeycombed, Sorem finds, but as the nodules age they become more compact, the pores fill in with clay, and the materials reorganize. He finds no clear age pattern in the layers, but in some samples the layers are thicker on the bottom of the nodule (the side in contact with the sediments).

On a finer scale the structure of many nodules is close to amorphous; they are composed of fine-grained but inhomogeneous materials that include some recognizable crystals of manganese and iron minerals, often segregated in discrete layers. Sorem finds that most nodule material gives no x-ray diffraction pattern at all, and the patterns that do appear are characteristic of crystal sizes less than a few micrometers.

Radiometric dating of nodules indicates that they grow very slowly. Growth rates between 1 and 100 mm per million years have been reported. By comparison, sediment accumulates on the ocean floor at a rate exceeding 1 m per million years even far from sources of continental debris and outside the equatorial zone of high biological productivity (where the rate of accumulation is much higher). Nodules are mostly found on the surface of the sediments or only partially submerged, however, and there is little agreement as to what keeps them from being buried. Some investigators believe that deep sea organisms that feed on protozoans nudge the nodules, while others believe that the protozoans themselves buoy up the nodules.

That living organisms do play a role in the development of the nodules seems to be clear. Work at Scripps Institution of Oceanography by J. Greenslate has revealed small tubular structures on the surface of carefully collected nodules, some of which had been built by a genus of deep ocean Foraminifera (*Saccorhiza*) (*3*). The tubular structures, many of which were made of ferromanganese material were easily destroyed (even by washing the nodule). Greenslate thinks this fragility explains why they had not been found on nodules brought to the surface by normal dredging procedures. The tubules and other smaller structures found on nodules from all parts of the Pacific show, Greenslate believes, that the surface of the nodule is home to many different protozoan organisms, making it perhaps the most densely populated site on the deep sea floor. Moreover, he finds remnants of similar structures within the interior of the nodules. On the basis of these observations, Greenslate suggests that nodules are formed around a skeleton of biotically derived tubules and chambers. Originally built on the nodule surface, these structures are later buried by other tubules and filled in with manganese precipitated by inorganic or bacterial processes and with clay and other debris.

Bacteria that oxidize and precipitate manganese and others that can reduce manganese oxides do exist, according to H. L. Ehrlich of Rensselaer Polytechnic Institute. The bacteria produce an enzyme system that catalyzes the reactions, he finds, and the reactions occur at the temperature and pressure of the deep ocean. Ehrlich believes that manganese oxides can precipitate and adsorb onto a growing nodule without bacteria but that the organisms accelerate the process through their catalytic role. The other constituents of the nodule, iron oxides and smaller amounts of copper, nickel, and other metals, probably precipitate inorganically, since they are known to adsorb strongly on manganese oxide. The bacterial reducing agents, he speculates, may be involved in the release of manganese and other elements adsorbed onto it from the sediments.

If biological structures built by communities of microorganisms are the basis around which nodules are formed, as Greenslate proposes, it may explain the occurrence of nodules in distinct patches and the relative similarity of nodules within a given patch. The variations in shape and composition from one patch of nodules to another may also be attributable to variations in the communities of microorganisms.

Where the metals found in the nodules come from and how they are concentrated are subjects of some debate. It is known that iron and manganese, along with other metals, are introduced into the oceans by submarine volcanic eruptions and as runoff from the continents. In oxygen-rich waters (away from continental margins), deposition of ferromanganese minerals is widespread on the ocean floor.

The immediate source of copper and nickel in the North Pacific band of nodules is less certain, but, according to G. Arrhenius of Scripps, these metals are concentrated from seawater by plankton and deposited in the sediments. There the decay of organic materials eventually releases the metallic ions, and they are transported to the surface of the sediments to be incorporated in the nodules. (Arrhenius and his colleagues point out that sediments in areas of nickel-rich nodules are depleted in the metal.) Others have proposed that metals in the nodules are concentrated directly from seawater.

If the underlying sediments are indeed the immediate source of metals for the nodules — and the preponderance of evidence seems to favor this hypothesis — then the high rate of accumulation of biologically derived sediments may well explain the high concentrations of copper and nickel in nodules near the equator. Relatively few nodules are found directly within the high-productivity belt (most are presumably buried because of the very high sedimentation rate), but those which are found, according to Arrhenius, do have high metal values. North of the belt, sediment accumulates much more slowly and the density of nodules is correspondingly higher.

The occurrence of a belt of metal-rich nodules also seems to be attributable to the geology of the region. Northward of the Clipperton Fracture Zone the water becomes much deeper, deep enough that calcium carbonate sediments — which make up much of the deposits farther south — dissolve, leaving primarily siliceous sediments. The removal of carbonate has the effect, Arrhenius believes, of increasing the concentrations of manganese, iron, copper, and other nodule metals in the sediments while keeping the net accumulation of sediment low enough to permit nodules to form in large numbers. It is on the siliceous clay that the best deposits appear to be found.

Study of the North Pacific nodule beds and their geochemistry has only begun. But enough is known to show that they are a unique phenomenon and, quite possibly, a mineral resource of considerable value.

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Prospects for Deep Sea Mining of Manganese Nodules

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The history of mining is replete with examples of recovery and extraction techniques whose development was stimulated by new ores. The discovery in some parts of the Pacific Ocean of manganese nodules that also contain nickel and copper in higher concentrations than most ores being mined today is having a similar effect. Whether the methods now being developed to dredge nodules from the deep seabed and to extract pure metals from the nodule ore will become the basis of a new mining industry is still uncertain—economic, environmental, and legal questions about the feasibility of deep sea mining remain to be answered. Nonetheless, development of what may prove to be a major new marine technology appears well under way.

The participants include both industrial concerns and governments. A special case is that of Howard Hughes' Summa Corporation and the U.S. Central Intelligence Agency, which together built what is conceded to be the Cadillac of deep sea recovery systems but whose plans for nodule mining are unclear. Leading the field in addition to Summa are Deepsea Ventures, Inc. (a Tenneco subsidiary), and Kennecott Copper Company, all of which are engaged in exploration and the development of mining and processing systems. Others include Ocean Resources, Inc., and the Canadian-based International Nickel Company (INCO). In Japan and Western Europe the national governments have taken an active role in partnership with industrial groups such as the Sumitomo group in Japan, an association headed by Metallgesellschaft AG and Preussag AG in West Germany, and the French Société le Nickel. The Japanese, in combination with Ocean Resources, Inc., have actively worked on the development of a mining system, while INCO, the Germans, and the French have so far emphasized exploration and process development.

The potential profits from deep sea mining operations will depend heavily on the metal content of the nodules, their size and abundance on the ocean floor, and the characteristics of the underlying sediments. Consequently, those interested in mining have spent considerable effort in exploring for rich deposits. The principal technique has been to scan the sea floor with an underwater television camera and to collect samples at periodic intervals for later analysis. Typical high grade deposits are reported to assay 27 to 30 percent manganese, 1.1 to 1.4 percent nickel, 1.0 to 1.3 percent copper, and 0.2 to 0.4 percent cobalt (although nodules with higher assays have been found) and to have about 10 kg of nodules per square meter.

The dredging methods now in use are limited to about 300 m, and to recover nodules from deposits at depths of 5000 m or more requires new techniques. Two principal types of deep mining systems are being developed. One, a mechanical system known as the continuous line bucket (CLB), consists of a long loop of cable to which specially designed dredge buckets are attached at intervals of 25 to 50 m. A traction drive (on the mining ship) moves the cable so that buckets descend into the ocean, are dragged across the seabed to scoop up nodules, and return to the surface to deposit their load.

A second, hydraulic recovery method consists of a length of pipe suspended from a mining ship; a sea floor device (dredge head) designed to collect nodules, screen out those larger than a certain size, and feed the rest to the bottom of the pipeline; and some means of pumping water up the pipeline with sufficient velocity (about 4 m/sec) to transport the nodules as well. The bottom device is either self-propelled or dragged across the bottom by the pipe string, depending on the design. Both conventional centrifugal pumps and compressed air injected into the pipe (air-lift pumping, in which the air bubbles provide enough buoyancy to raise the entire column of water and nodules) are being considered.

Mining Nodules Will Not Be Easy

Either system must contend with the difficulties of operating a mining ship in all kinds of weather, of controlling an extremely long length of pipe or cable, and of collecting nodules from a seabed of uncertain and variable physical properties. According to John Mero of Ocean Resources, Inc., the CLB system has the advantage of simplicity and flexibility, since it has no underwater machinery, can recover nodules of any size, and does not need to be designed for a specific depth and type of sediment as do hydraulic systems. Moreover, he claims that the system will cost much less than the more complex hydraulic equipment, although most other marine engineers dispute his estimates.

Mero admits, however, that such measures as shark-proofing the polypropylene cables and using two surface ships instead of one to keep the bucket loop from becoming entangled when the system is shut down may be necessary. A more serious difficulty is that the buckets must actually pick up a good load of nodules but little sediment for the system to be economic, and there is no way to control how the buckets interact with the bottom. Perhaps the most fundamental limitation of the CLB system, according to critics, is that cables are not strong enough and cannot be moved rapidly enough to mine 3 or 4 million tons of nodules per year with a single unit—a capacity that hydraulic systems can achieve and that many companies believe to be the economic minimum.

Hydraulic systems, on the other hand, require more elaborate gear, and a ship specially equipped to handle a long string of pipe. Centrifugal pump systems must be electrically or hydraulically powered underwater, a tricky and trouble-prone arrangement in the marine environment. Air-lift systems, however, are less efficient and must cope with the complexities and potential instabilities of three-phase flow (the pipe will simultaneously contain water, air, and nodules moving together). The bottom device, the key to a successful mining system, must traverse or sweep the loosely compacted sediments of the sea floor without becoming bogged down. Hydraulic systems are limited to recovering only part of the available resource, since larger nodules that might block flow in the pipe must be left behind. And the complete system may be expensive.

The advantages and disadvantages of each system depend in part on who is doing the talking, of course, and in a competitive arena such as deep sea mining, no company will disclose precise details of its own system, so that much of the available information comes from competitors. Claims and counterclaims are therefore to be regarded with some caution.

Experience with both systems is limited.

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The CLB system was tested in 1970 by an agency of the Japanese government and again in 1972 by a consortium headed by Ocean Resources, Inc. Deepsea Ventures has successfully tested an air-lift hydraulic system in relatively shallow water and plans deep-water tests in 1975. The Hughes organization has built the first full-size prototype of a mining ship.

There is general agreement that Hughes bought the best expertise available. His system was designed by the Lockheed Missiles and Space Company, who have an impressive record of experience with undersea technology, and by Global Marine, Inc., who operate (for the National Science Foundation) the deep sea drilling ship *Glomar Challenger* that has pioneered mid-ocean drilling techniques. Indeed the Hughes mining ship is essentially a more sophisticated version of the *Glomar Challenger*.

The hydraulic mining system being developed by Deepsea Ventures, Inc., includes a much smaller collecting device that is essentially a passive dredge head dragged across the ocean floor on the end of a pipeline. Sets of tines much like those on a rake collect the nodules, screen out those that are oversize, and help to separate the nodules from the sediment. An air-lift system is used to bring the nodules to the surface. Because of its simplicity, the system (it involves no underwater pumps or other machinery) has the advantage of low cost and reliability of operation, according to Raymond Kaufman of Deepsea Ventures. Because of the relatively crude collecting device, however, it must be carefully designed to match sea floor conditions at a particular mine site. And because the dredge must be towed across the bottom without exerting undue stress on the pipeline, the mining area must be very carefully surveyed before mining can begin.

Another difference is in capacity. Deepsea Ventures intends to recover about 1 million tons of nodules per year, whereas the Hughes team has claimed to be aiming for 3 to 4 million tons a year or more. The difference is related to the metals which are the ultimate aim of the mining efforts. Hughes, along with Kennecott, INCO, and apparently many others interested in deep sea mining, believes that copper and nickel will be the prime metals obtained from the nodules. To obtain enough of these metals for profitable operation, large tonnages of nodules are needed. Deepsea Ventures, on the other hand, is planning to extract and sell manganese and cobalt as well, rather than consign them to the scrap heap. Because there is so much manganese in the nodules, fewer are needed to yield a marketable amount of metals. The decision to include manganese influences not only the design of Deepsea Ventures' mining and processing system but also the company's business strategy, since they must find new markets (in the steel industry, for example) for manganese metal.

Most other companies are moving very slowly. Kennecott, for example, is known to be designing a hydraulic system. The Germans have published research on hydraulic mining designs, but are not far along in developing a system. The syndicate of companies which owns the rights to the CLB system will probably raise the money for a final test of that technique in the next couple of years, according to Mero, but no definite plans exist. INCO is maintaining an interest in both types of systems but has made no commitment to either.

Work on methods of processing the nodule ore is much further advanced. Kennecott has operated several pilot plants and is proceeding with the design of a full-scale system. Deepsea Ventures is nearly as far along. European companies, especially in Germany, have large research efforts on processing under way. Since a processing plant is expected to account for more than half of the cost of a complete nodule-mining operation, the stakes in choosing the best extractive method are high and four or five processes are being investigated.

Straightforward methods of extracting metals do not work because of the nature of the nodules. The manganese oxide and iron oxide minerals that are the main metal constituents of the nodules are extremely fine-grained. Consequently, physical means of separating the metals have not proved successful. Smelting the nodule ore has been tried, also without great success. Although it is possible to reduce the oxides by heating in a furnace to a temperature of about 1500°C, the result is an alloy of various metals (including iron) that is difficult to separate further. In consequence, chemical (hydrometallurgical) separation methods seem to be of most interest to the industry.

In the chemical approach, the nodules are partially or completely dissolved and the metals separated from solution. The task is made easier for those who seek to recover only nickel and copper, since these metals are predominantly found in association with the manganese minerals (adsorbed onto them or embedded in the crystal lattice). Cobalt is found mostly in the iron. Hence several different reagents, selective leaching techniques, and reducing treatments can be utilized, depending on the desired product.

Several investigators have tried leaching the nodule material with sulfuric acid. The acid readily dissolves the copper, nickel, and cobalt, but also some manganese, iron, and undesirable trace elements. Large quantities of acid are required, presumably due to the presence of basic material trapped in the nodule. The consensus is that the technique is not selective enough for commercial use.

A second selective leaching procedure is based on ammonia in conjunction with an ammonium salt (ammoniacal solution). First the oxide compounds are reduced to a lower oxidation state by roasting with a gaseous reagent such as carbon monoxide. Then the ore is treated with ammoniacal solution, sometimes under conditions of increased temperature and pressure. According to D. W. Fuerstenau of the University of California at Berkeley, this process can dissolve more than 80 percent of the copper and nickel and about 50 percent of the cobalt, leaving the manganese and iron essentially intact. The process is similar to one used to extract nickel from laterite ores. Kennecott has obtained several patents for ammoniacal leach processes and is believed to be basing its commercial plans on a version of this method.

A third process involves dissolving the entire nodule. The ore is roasted with sulfur dioxide to reduce the oxides and then leached with water. The resulting sulfate salts are separated to obtain the metals (a tricky process about which little has been published). Alternately, sulfur dioxide in water is used directly to dissolve the nodule (a reaction that is reported to go very quickly). In either case, the manganese is dissolved whether it is ultimately desired as a product or not. The process is particularly attractive to companies that have sulfur dioxide to dispose of (from, for example, copper smelters), but it is also regarded as a difficult process in which to control pollution.

A fourth process, also one in which essentially the entire nodule is dissolved, is that developed by Deepsea Ventures as the basis of its commercial plans. The crushed nodules are reacted with hydrogen chloride at temperatures such that most of the metals except iron are converted to soluble metal chlorides. (As a by-product, hydrogen chloride is converted into chlorine gas.) The metal chlorides are then dissolved in water and separated into aqueous solutions of nickel, cobalt, and copper salts by a liquid-ion-exchange process. From these solutions, pure metal is produced in electrolytic cells. Manganese is recovered separately. According to P. H. Cardwell of Deepsea Ventures, the advantages of the process include the high recovery rate (better than 95 percent of the metal content of the ore is recovered) and the fact that the solvents used are recycled, thus minimizing pollution.

Environmental Effects a Concern

Nodules are found in areas of the ocean that are in many respects biological deserts, but that does not mean mining will have no effect on the ocean environment. The potential problems include local disruption of the sea floor ecosystem, and distribution of sediment particles—some of which may remain suspended for a year—throughout the water column. The sediment might alter chemical balances both in the more populated surface waters and below, and as it settles out may bury organisms that live on the sea floor. Many oceanographers do not believe that mining itself will do much permanent damage to the oceans as a whole, however, because of the relatively small areas to be affected, but they point out that it may destroy sediment records of scientific interest. More serious environmental effects may come from processing the nodules, especially if, as some have suggested, second-generation plants are built to operate at sea. Even on land, operations that involve discarding all but the copper and nickel must dispose of millions of tons of residues that contain manganese and other toxic metals in oxide form.

The impact of the new source of metals on world markets is also a controversial subject. At one extreme, deep sea mining optimists like Mero forecast a drop in metal prices within 10 years after production starts and the closing of many land mines within 20. Others, such as A. J. Rothstein and Kaufman of Deepsea Ventures, maintain that copper prices will not be affected at all in the foreseeable future and that only for cobalt are the nodules likely to cut into prices or land-based production significantly. An analysis prepared for the World Bank points out that mining of enough nodules (about 6.5 million tons) to meet the world demand for cobalt in 1967 would have provided 22 percent, 0.9 percent, and 13 percent, respectively, of the world demand for manganese, copper, and nickel. The analysis also assesses the economics of deep sea mining as uncertain, largely because of the still unknown costs of the mining itself (estimates range from about $3 to $30 per ton of dry nodules at dockside). It concludes that exploitation of the nodules could reduce the dependence of industrialized countries on imports of metals and could seriously affect a few of the developing countries that depend on exports for revenue.

Commercial mining operations are not likely to begin before 1977 (it takes 3 years to build a processing plant and none are now under construction), if then. The prospects probably depend in large part on what happens to the international political and legal argument over the law of the sea, although several companies have hinted that they might force the issue by mining even in the absence of an international convention.

At present almost all of the major companies are actively negotiating for partners to share the estimated $250 million investment (and the risks) of a deep sea mining venture. Early in 1974, Kennecott, along with four other companies, announced a 5-year, $50-million research program to determine mining feasibility. In any case, there appears to be growing conviction in the industry that deep sea mining is gathering momentum, that manganese nodules are indeed on the verge of commercial exploitation.

Electronic Materials: Functional Substitutions

A. G. Chynoweth

One of the most dramatic of recent technological achievements is the hand-held electronic calculator. In its simplest versions, costing only a few dollars, it performs all the functions that were previously performed by the electromechanical desk-top calculator. In more sophisticated versions it does much more, performing comparably to what formerly required moderately sized computers. Quite apart from its primary purpose of making increased mathematical capabilities more widely available, the savings in materials relative to older equipment are obvious. So the question arises, whether such kinds of technological developments could help us to meet some of the limitations on supplies of natural resources that may lie ahead. The answer is of necessity open-ended; nevertheless, the needs for more in-depth studies of some of the factors—resources, technical, economic, and social—raised by this question warrant further attention.

The hand calculator is only a recent, well-publicized example of the revolution that is being steadily brought about by solid state electronics. While some solid state devices existed in the 1920's and 1930's, such as the original cat's whisker diodes and selenium rectifiers, the solid state revolution really had its beginnings in the discovery of the transistor in 1947. This three-terminal device essentially opened up the whole of electronics technology, previously based on vacuum tubes, to solid state components. The substitution of the transistor for the vacuum tube was immediately seen as a materials- and energy-saving substitution in addition to the improved technical performance it made possible. In many ways, the transistor did for man's brain what the earlier invention of the steam engine had done for man's brawn. It can be regarded as the instigator of the Second Industrial Revolution.

The transistor led, in turn, to the development of integrated circuits in which not simple discrete electronic components are linked together but in which the whole circuit, often consisting of thousands of transistors, resistors, capacitors, and interconnections, is fabricated essentially as one, highly processed, minute piece of material. These integrated circuits, nowadays the heart of nearly all electronic equipment, including the hand calculators, also seem to offer enormous material and energy savings over their older counterparts.

Functional Substitutions

The sort of substitution represented by transistors for vacuum tubes, and by integrated circuits for calculating machines, is often referred to as a functional substitution (as distinct from a material substitution). In these substitutions, a completely different approach to performing a needed function is found. For example, adhesives can be used instead of nuts and bolts for joining. Jet engines replace piston engines and propellers in aircraft. Telephones can replace mails for transmitting information. Nuclear reactors replace boilers fired by fossil fuels. Functional substitutions can lead to the revision of consumption patterns for materials and energy and can inspire the creation of entirely new industries.

The transistor, for example, has led to technological development of computers, missile-control systems, and a broad range of industrial, medical, and leisure products. And in nearly every case, the substitution of solid state electronics for older techniques appears to have led to considerable savings in the amounts of material needed for manufacture and the energy required to operate the equipment. To some extent the new development can be regarded as the substitution of light industry for heavy industry, of information technology for machinery.

Nature of Electronic Materials

Increasingly, electronic materials are included alongside metals, ceramics, and polymers as a major material division in the field of materials technology, in spite of the different ways in which electronic materials are used. Whereas metals, ceramics, and plastics are nearly always used in structural parts that have mechanical functions, electronic materials (as their name implies) are used to perform electromagnetic, including optical, signal processing functions. In the hand calculator, the calculation is performed electronically; in the older desk calculator it is performed mechanically via levers, shafts, and gears. Likewise, electronic mechanisms are replacing mechanical ones in watches. The overall functions are the same, but an electronic technology has been substituted for a mechanical one.

Stemming largely from the transistor discovery, and as indicated in Fig. 1 by the schematic tree (*1*), there is a growing variety of electronic materials, a term that can be taken to embrace semiconductors, conductors, superconductors, magnetic metals and crystals, dielectrics, piezoelectrics, pyroelectrics, ferroelectrics, lasers, electrooptical and magnetooptical materials, luminescents, and others. Their names often belie their main functions. They can be made to perform a vast range of information or signal-handling operations, such as signal generation, modulation, detection and amplification, memory and display, switching, and logic. And in performing such functions they provide a gold mine of technological options for the development of, for example, communications, computers, and control systems.

If we accept for the present that electronic materials and solid state electronics offer prospects of significant materials and energy savings and in so doing may be more part of the solution to materials scarcity problems than a cause, two principal questions arise: (i) Are electronic materials themselves vulnerable to scarcities of raw materials? and (ii) In which technological sectors can electronic materials mitigate problems of materials scarcity?

Effects of Materials Scarcities on Solid State Electronics

With regard to the first question, most of the elements in the periodic table are used in some kind of electronic equipment. In the telephone alone, 42 of the 92 elements provided by nature (Table 1) are present as constituents of 35 types of metals and alloys, 14 types of plastic, 12 varieties of adhesives, and 20 different semiconductor devices. Supplies of many of the elements used in the telephone, as in other electronic equipment, can be considered as vulnerable either to worldwide shortages

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← *Courtesy General Electric Research and Development Center, Schenectady, New York*

(mercury and tin, for example) or vulnerable to the export policies of foreign nations (gold, palladium, chromium, for example).

Offsetting these vulnerabilities, however, is the fact that the quantities used in electronic equipment are usually relatively small. Furthermore, compared with other uses for materials, electronics usually carries a large value-added factor so that relatively large, scarcity-driven increases in materials prices can be more readily carried than in many other technologies. For example, finding a substitute for soldering tin may prove very difficult whereas substitutes may be found for tinplate in containers and for bronze alloys in bearings. Thus if tin becomes scarce and relatively too expensive, the substitute products would leave the available tin for more critical electronic uses.

But what if it does become necessary to find a substitute for one of the materials used in electronic equipment or in integrated circuits? Such items are usually assemblies of intimately interacting materials, each material being carefully chosen and developed to optimize the overall performance of the component. In consequence, even a minor change in one of the materials used within a complex component might have a major effect on the overall quality or performance of the component. In such circumstances, substitution of one material for another may be difficult or even impossible. This is particularly true for equipment in which materials performance has been pushed to the limit.

As a general rule, the simpler the application, the easier it is to find a substitute material. If a society's needs are sufficiently simple, the thesis of infinite substitutability might be tenable—materials are likely always to be available for simple products such as utensils for cooking and eating, for clothing, and for simple dwelling structures. But the more a society depends on complex and sophisticated equipment, the more vulnerable it is to scarcities of certain key materials, even if these are used in very modest amounts. Nevertheless, among the more sophisticated technologies, electronic equipment will often retain an advantage over other technological sectors because of the relatively small amounts of material it requires.

There are some materials for which the electronics and electrical industries are the dominant consumers. Copper, for example, is the electrical conductor material par excellence. The electronics and electrical industries account for 54 percent of U.S. consumption. But we are likely to experience shortages of copper over the next 50 to 100 years, even though, in the nearer term, domestic resources are large, worldwide reserves appear to be good, and the multiplicity of sources minimizes the U.S. vulnerability to actions by foreign governments. Also, a strong and well-established recycling technology for copper exists. But perhaps most important for the longer term, there is an abundant substitute, aluminum. While the substitution of aluminum for copper in wires and cables is by no means as straightforward or inexpensive as many people might think, nevertheless it is possible. There is an energy penalty, however; the energy required to produce aluminum can be several times that required to produce the same weight of copper.

Other metals for which the electronics and electrical industries are the dominant users in the United States include beryllium (62 percent), gallium (> 80 percent), germanium (60 percent), indium (85 percent), tantalum (55 percent), and yttrium (86 percent). In addition, there are several elements which find some critical use in these industries and whose abundance or source of importation (or both), along with a lack of domestic reserves, may cause concern. The general supply of these elements is summarized in Table 2. Some of the major applications in the electronics and electrical industries for these elements and also some possible substitutes are listed in Table 2.

Examination of the data shown in Tables 2 and 3 leads to the reassuring conclusion that, overall, the electronics industry is not very vulnerable to materials shortages. No sudden, dramatic shortages are foreseen for any of the key elements; besides, in many cases, the quantities required for electronics are modest. Furthermore, material or functional substitutes are available in many instances.

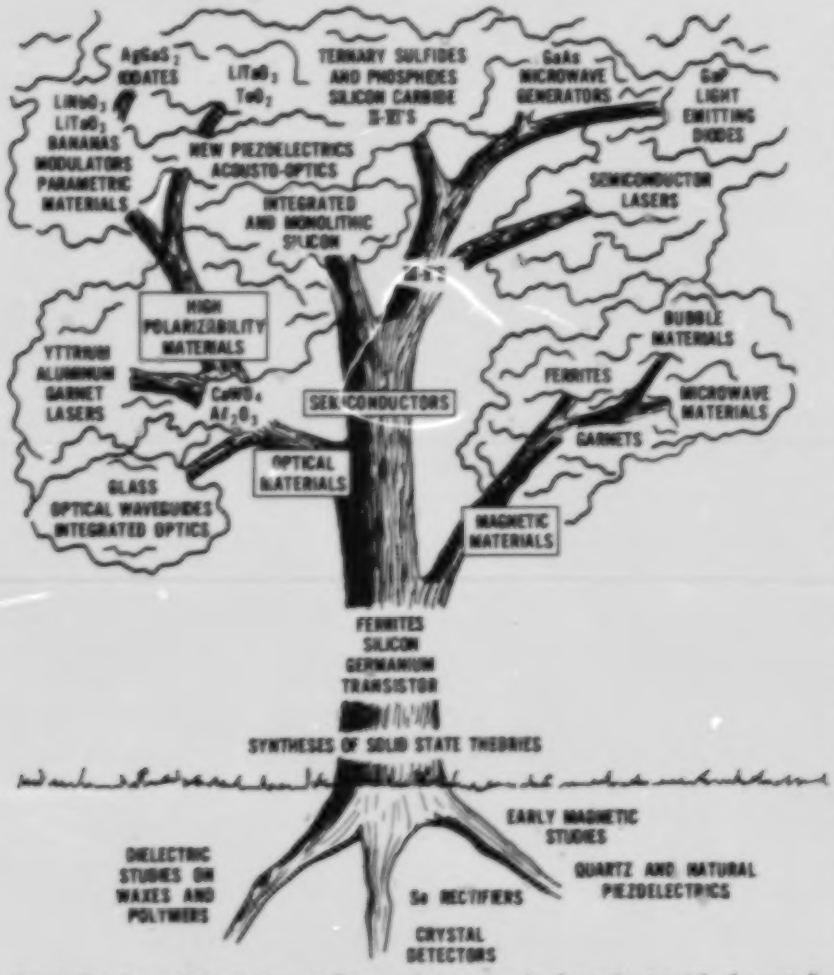

Fig. 1. The electronic materials tree. Representing progress in electronic materials, the roots lie in the basic sciences and in early studies of materials; the trunk signifies the development of the transistor; the branches represent those areas of current electronic materials progress—semiconducting materials more complex than those used in early transistors, magnetic materials now being used in computer memories, and optical materials for use in light-emitting, transmitting, and modulating devices.

For the integrated circuit, which is the heart of electronics, the prospect seems even more reassuring, because it is based on silicon—the most abundant of all elements except oxygen. And since such small quantities of silicon are needed, this suggests that man can plan on using solid state electronics extravagantly and indefinitely. However, there may be, eventually, other constraints regarding some of the more exotic materials used in conjunction with the principal semiconductor materials, the chemicals used for processing them, and the methods used for preparing the necessary ultrapure materials.

Except for certain special applications, a substitute for silicon is neither likely nor necessary. Rather, emphasis will be the other way round. In comparison with other semiconductor materials silicon always offers a relatively simpler technology. "If you can do it with silicon, you will." However, other semiconductors, particularly compounds of group III elements in the periodic table, such as gallium, aluminum, and indium, with group V elements, such as antimony, arsenic, and phosphorus, offer many optoelectronic and microwave properties that silicon cannot. But again, the quantities of material envisaged are relatively small, and overall it appears that shortages of basic semiconductor materials will not occur for the foreseeable future.

While substitution may not be a pressing problem with the semiconductor materials, it may become more so with some of the other electronic materials. As judged from the following examples, substitution, at least up to a point, would appear possible in many of these cases.

Electronic-grade mica is one of the scarcest of all materials. Traditionally it has been used in capacitors and as insulating supports in vacuum tubes. Nowadays there are various other materials suitable for these functions, but if a material were needed closely comparable to mica in its dielectric and mechanical properties, including its cleavage capabilities, such a material appears available. It is potassium niobate, a material that can be prepared by the same Czochralski pulling technique used for growing silicon crystals. Its mica-like properties were discovered as a by-product of an exploratory program in which new, nonlinear optical materials for electrooptical devices were being sought.

Brazil has been essentially the sole source for electronic-grade quartz used in piezoelectric frequency standards and filters. At present, such quartz is not used directly for making devices, but is crushed and used as nutrient for the hydrothermal growth of "synthetic" quartz. Recently, the price of Brazilian quartz was raised more than tenfold. This action stimulated searches for alternative sources of quartz of suitable quality, but again, in the hypothetical situation that this material became completely unavailable, it is reassuring to know that there are potential substitutes sitting on the shelf. Among the best of these is lithium tantalate, another crystal that can be grown by the Czochralski technique. Piezoelectrically it is even more efficient than quartz and has excellent temperature stability. Like potassium niobate, it was a spin-off from the optical material exploratory program. But single-crystal piezoelectric materials are not the only means of making electromechanical resonators. A feasible alternative is to use thin film oxide (such as zinc oxide) piezoelectric transducers mounted on metal resonator blocks.

Magnetic alloys are used in many varieties of electromagnetic switches and relays and in certain memory devices. Although the principal ingredient is usually iron, customarily cobalt and nickel are used in these alloys together with other elements such as vanadium, niobium, molybdenum, and chromium. Again, substitutes in the form of ferrites (oxides of iron), or other substances, such as yttrium, are potentially available although, in most cases, considerable equipment redesign would be necessary to incorporate them. Various ferrites are already used widely in electronics for high-frequency transformer and inductor cores, computer memory cores, and for magnetic recording tape.

Precious metals are important to a number of electronic components and integrated circuits. Gold is frequently used for leads and thin film conductor strips in integrated circuits because, among other properties, it has long-term stability and corrosion resistance qualities that are particularly important in microcircuits where dimensional or compositional changes on even the microscopic scale can be serious problems. However, other metals, such as aluminum, can be used for thin film conductors if suitably protected from corrosive environments.

Palladium offers an instructive case history of substitution. In electronic equip-

Table 1. Elements in the telephone handset (*3*).

Element	How used
Aluminum	Metal alloy in dial mechanism, transmitter, and receiver
Antimony	Alloy in dial mechanism
Arsenic	Alloy in dial mechanism
Beryllium	Alloy in dial mechanism
Bismuth	Alloy in dial mechanism
Boron	Touch-Tone dial mechanism
Cadmium	Color in yellow plastic housing
Calcium	In lubricant for moving parts
Carbon	Plastic housing, transmitter steel parts
Chlorine	Wire insulation
Chromium	Color in green plastic housing, metal plating, stainless steel parts
Cobalt	Magnetic material in receiver
Copper	Wires, plating, brass piece parts
Fluorine	Plastic piece parts
Germanium	Transistors in Touch-Tone dial mechanism
Gold	Electrical contacts
Hydrogen	Plastic housing, wire insulation
Indium	Touch-Tone dial mechanism
Iron	Steel, magnetic materials
Krypton	Ringer in Touch-Tone set
Lead	Solder in connections
Lithium	In lubricant for moving parts
Magnesium	Die castings in transmitter, ringer
Manganese	Steel in piece parts
Mercury	Color in red plastic housing
Molybdenum	Magnet in receiver
Nickel	Magnet in receiver, stainless steel parts
Nitrogen	Hardened heat-treated piece parts
Oxygen	Plastic housing, wire insulation
Palladium	Electrical contacts
Phosphorus	Steel in piece parts
Platinum	Electrical contacts
Silicon	Touch-Tone dial mechanism
Silver	Plating
Sodium	In lubricant for moving parts
Sulfur	Steel in piece parts
Tantalum	Integrated circuit in Trimline set
Tin	Solder in connections, plating
Titanium	Color in white plastic housing
Tungsten	Lights in Princess and key sets
Vanadium	Receiver
Zinc	Brass, die casting in transmitter, ringer

ment its major use is as a contact material for the electromagnetic relays used by the millions in telephone networks. On account of the high cost of palladium relative to other metals, suitable substitutes have been sought since the 1920's, but the only acceptable one so far found is an alloy of 60 percent palladium and 40 percent silver. (Silver is of the order of 1/20 the price of palladium, reflecting its relative availability.) All of the countless other metals and alloys investigated over the last 50 years or more have been shown to be less satisfactory in some physical, chemical, or engineering respect as a direct substitute for palladium. This is not to say that contacts made with other metals would not work, but that their performance and reliability would generally be inferior.

The electromagnetic relay or switch will be useful in communications systems for many years to come, but at the same time newer electronic switching systems, which do not rely on relays, will be steadily taking over, eventually eliminating this need for palladium.

This brief review of some examples of materials substitution in electronic technology, both current and potential, reinforces the impression that this technology is not particularly vulnerable to materials shortages either because of the relatively minute amounts of material used or, more importantly, because of the enormous versatility and adaptability of the science of electronic materials.

Table 2. Elements important to the electronics and electrical industries, listed in decreasing order of percentage of all consumption accounted for by these industries. Data from (*4*).

Material	Electronics use (%)	U.S. annual consumption		Sources of U.S. imports		U.S. reserves/ U.S. annual consumption (years)	World reserves/ annual production (years)	Ratio of world resources to reserves
		Total (tons)	Percent imported	Country	Percent			
				Elements				
Yttrium	86	92	?	Australia	53	?	150	Probably very large
				Malaysia	44			
				Other	3			
Indium	85	?	?	Canada	44	?	25	>2
				U.S.S.R.	14			
				Peru	11			
				Japan	9			
				Other	22			
Gallium	>80	~20	80	Switzerland	72	?	7,500	Very large
				United Kingdom	4			
				West Germany	4			
				Other	20			
Beryllium	62	312	20 (1969) 75 (1973)	Brazil	64	?	?	?
				Republic of South Africa	13			
				Argentina	7			
				Uganda	5			
				Other	11			
Germanium	60	20	17 (1969) 33 (1973)	U.S.S.R.	40	?	?	?
				Belgium	17			
				Japan	13			
				Czechoslovakia	9			
				Other	21			
Tantalum	55	600	100	Canada	30	~0	85 (Non-Communist source)	Limited
				Brazil	22			
				Zaire	14			
				Other	34			
Copper	54	2,350,000	25	Canada	31	35	50	~3
				Peru	27			
				Chile	22			
				Republic of South Africa	6			
				Other	14			
Platinum group	39	60	~100	United Kingdom	39	2	120	2-3
				U.S.S.R.	32			
				Republic of South Africa	12			
				Other	17			
Mercury	33	[illegible]900	~85	Canada	59	7	20	~0
				Mexico	17			
				Spain	8			
				Italy	5			
				Other	11			
Cobalt	28	9,400	100	Zaire	45	3	100	~2
				Belgium	29			
				Norway	8			
				Canada	6			
				Other	12			
Gold	27	250	~85	Canada	51	10	23	?
				Switzerland	24			
				Burma	9			
				United Kingdom	3			
				Other				

Solid State Electronics: Materials Conservation via Miniaturization

While conventional electronic components—from cathode-ray tubes to crossbar switches, from klystrons to magnetic disk and tape memories—may not figure as massive consumers of materials when compared with, say, transportation equipment, they are nevertheless significant consumers of certain materials, as was discussed above. But a salient lesson of the substitution of transistors for vacuum tubes is the enormous potential that functional substitutions with solid state devices present for materials and energy conservation through miniaturization.

Fresh examples of miniaturization in solid state electronics continue to occur. Nowadays, an integrated circuit based on a silicon chip less than a quarter of an inch square may incorporate many thousands of transistors and associated circuit elements. This is a far cry from the early, discrete transistor of 20 years ago. Yet further miniaturization of integrated circuits, enabling even higher packing densities, is still expected. For example, the widths of conductor stripes, now typically a few micrometers, may eventually be reduced approximately tenfold by the development of ion and electron beam methods and plasma processing methods to replace the photographic techniques now commonly employed.

Other new devices, largely based on in-

Material	Electronics use (%)	U.S. annual consumption		Sources of U.S. imports		U.S. reserves/ U.S. annual consumption (years)	World reserves/ annual production (years)	Ratio of world resources to reserves
		Total (tons)	Percent imported	Country	Percent			
Silver	25	5,000	55	Canada	58	>7	18	>3
				Peru	20			
				Mexico	8			
				Honduras	5			
				Other				
Tin	15	56,000	~100	Malaysia	64	0.1	17	?
				Thailand	27			
				Other	9			
Aluminum	14	6,600,000	10	Canada	76	?	Abundant	Abundant
				Other	24			
Nickel	12	195,000	~90	Canada	82	1	65	Large
				Norway	8			
				Other	10			
Tungsten	10	7,750	56	Canada	61	10	30	~2
				Peru	9			
				Australia	5			
				Mexico	5			
				Other	20			
Antimony	7	39,500	50	Mexico	18	2	60	1-2
				China	16			
				Japan	13			
				United Kingdom	13			
				Other	40			
Lead	6	1,550,000	20	Canada	29	35	40	~1000
				Peru	21			
				Australia	21			
				Mexico	12			
				Other	17			
Rare earths	4	13,700	13	Australia	53	370	700	3-4
				Malaysia	44			
				Other	3			
Niobium	<4	1,000	0	Brazil	62	0	600	?
				Canada	16			
				Nigeria	14			
				Other	8			
Manganese	~2	1,900,000	85	Gabon	35	0	60	Very large
				Brazil	33			
				Republic of South Africa	7			
				Zaire	7			
				Other	18			
Zinc	—	1,520,000	40	Canada	48	20	20	~40
				Australia	10			
				Japan	9			
				Peru	8			
				Other	25			
				Other materials				
Mica (sheet)	~95	2,800	~100	India	79	~0	?	?
				Brazil	14			
				Malagasy Republic	3			
				Other	4			
Quartz (crystal)	100	150	100	Brazil	95	?	?	Limited
				Other	5			

Table 3. Some principal uses of elements important to the electrical and electronics industries and some possible materials substitutes.

Material	Uses in electronics	Materials substitutes
	Elements	
Yttrium	Color television phosphors	Other rare earth phosphors
	Magnetic materials	Some other rare earths
Indium	Semiconductors	
	Solders	Tin, lead, bismuth, cadmium
Gallium	Semiconductors (particularly, light-emitting diodes)	No equivalents
Beryllium	Electrical connector alloys	Phosphor bronze
	Springs	Phosphor bronze, spinodal copper alloys
Germanium	Semiconductors	Silicon
	Optical glass	Boron
Tantalum	Solid electrolytic capacitors	Aluminum, niobium
	Thin film circuitry	Hafnium
Copper	Signal transmission lines	Aluminum, glass optical waveguides
	Electrical conductors	Aluminum
Platinum group	Contact materials	Silver, gold, and their alloys
	Thin film conductors	Aluminum, tungsten
Mercury	Wetted contact relays	None satisfactory
	Arc rectifiers	None satisfactory
	Batteries	Various
	Lamps	Sodium
Cobalt	Magnetic alloys	Nickel, iron
	Ferrites	
Gold	Platings, contacts	Various, but inferior
	Thin film conductors	Tantalum, aluminum
Silver	Contact alloys	
	Conductors	Copper, aluminum
	Conductive paste	
Tin	Solders	Lead (partial)
	Copper alloys	Aluminum bronzes, stainless steel
	Superconductors	Other A-15 compounds
Aluminum	Conductors	
	Insulating ceramics	Various
Nickel	Magnetic alloys	Cobalt, iron
	Spring alloys	Various
	Ferrites	
Tungsten	Light filaments	
	Evaporator filaments	
	Metallizations	Aluminum
Antimony	Semiconductors	
	Fire retardants	Halogenated aromatics
	Solders	Tin, lead, bismuth, cadmium
	Cable sheathing	Calcium
	Batteries	Calcium
Lead	Batteries	Nickel-cadmium, and others
	Cable sheathing	Polyolefins
	Solders	
Rare earths	Magnetic crystals	Various rare earths
	Optical crystals	
	Phosphors	
Niobium	Magnetic alloys	Iron, nickel, cobalt
	Superconductors	Other A-15 compounds
Manganese	Ferrites	
	Magnetic alloys	
Zinc	Ferrites	
	Spring alloys	Various
	Batteries	Various
	Other materials	
Mica (sheet)	Dielectric	Potassium niobate
Quartz (crystal)	Filters, transducers	Lithium tantalate
		Mechanical resonators

tegrated circuit technology but which portend materials savings, include bubble domain memories, charge-coupled devices, and Josephson junction logic circuits. These devices or circuits are able to process and store bits of digital information. In the bubble domain device, a bit is represented by the magnetization state of a small region, or domain, of a crystalline or amorphous metal magnetic material. By suitable arrangements of externally applied driving fields, these domains can be moved about and used to perform sequential and associative memory and logic operations. Including associated circuitry, bubble domain memories have already been built which offer nearly half-a-million bits storage capacity in a few cubic centimeters, a considerable reduction in volume (and weight) from that required to achieve the same capacity using magnetic drums or disks.

Charge coupled devices (CCD), in which the information is stored as an excess or absence of electronic charge under a given electrode on a semiconductor, offer similar dramatic reductions. By means of suitable sequences of driving voltages, the charge state can be transferred along an array of semiconductor junctions thereby allowing the device to be used as a sequential or shift register. In a comparison of the potential of CCD's with magnetic drums, it has been estimated that for a usable capacity of more than 8 million bits, the CCD's offer approximately a tenfold reduction in weight (and volume) and nearly a hundredfold reduction in the required operating power. The CCD's also promise another dramatic development—a miniature television camera—in which an optical image is focused onto the CCD junction array and the impressed charge pattern is read out sequentially as in a television raster. Such a camera, with an FM (frequency modulation) transmitter making it a portable "walkie-lookie," need be no bigger than ordinary photographic cameras.

Josephson junction devices that exploit the peculiar switching properties of thin film superconductor structures potentially offer further increases in operational speed and packing density over integrated circuits. They present the possibility of another way of performing computer and logic operations that may be close to fundamental lower limits in power requirements.

An area in which functional substitution by solid state electronic components is rapidly occurring concerns electric indicator lights. Light-emitting diodes and liquid crystal displays are substituting for incandescent lights in a widening range of alpha-numeric and visual display applications, again with a much lower material

content and operating power requirement.

Just as the transistor substituted for the vacuum tube at lower frequencies, so at microwave frequencies we see the relatively small Gunn and Impatt diodes substituting for much more massive components such as klystrons, magnetrons, and traveling wave amplifiers.

And hard on the heels of integrated circuit technology is optical electronics, which promises to establish this technology as a major factor in electronics. Information is transmitted as optical rather than electrical signals. The signals are generated and detected by semiconductor junction devices—lasers, light-emitting diodes, and photodetectors—and transmitted along optical fiber light guides. The light guides, made of very pure glass, no thicker than a human hair, functionally substitute for the signal-carrying purposes of copper wires and coaxial cables. Light guides will probably find an increasing array of applications, from interoffice trunk lines in telephone networks to high-speed digital links in computers and large switching machines, from communication and control systems on board aircraft and ships to wide-band local services to telephone subscriber premises. Besides potentially offering improved performance and costs relative to conventional transmission methods, optical fibers are attractive in that their principal ingredients are silicon and oxygen, the two most abundant elements on the earth.

Increasing the Productivity of Electronic Equipment

The above examples of current and potential functional component substitutions reaffirm the conclusion that such substitutions for more conventional components can offer considerable materials and energy savings in the components themselves. But another very significant way in which such savings can occur is by increasing the productivity of electronic equipment. Telecommunications networks illustrate this point.

It would be impossible to provide today's volume of telecommunications traffic if it all had to be carried by wires and cables—the requirements for copper alone would be prohibitive, let alone the associated needs for additional switching machines and buildings in which to house them. As the volume of trunk-line traffic increases, it becomes advantageous to multiplex many signals on to a single transmission line rather than provide separate lines for each signal. Further productivity can be obtained by time division in which a given frequency band is shared in a rapid, repetitive sequence by several different signals. Voice signals, converted into a series of digital pulses, can be compressed, timewise, and transmitted as a short pulse train. At the receiving end the pulse train is expanded again and converted to analog to reconstitute a voice signal. By means of such compression and time-sharing, the productivity of transmission lines can be increased many times over what it would be if they carried simple, real-time analog signals alone. Another promising way of squeezing more productivity out of transmission lines is to avoid sending redundant signals along them; for example, in transmitting a video signal, the requirement for transmission capacity can be considerably reduced if only the changing elements of the picture are transmitted.

These and many other tricks with transmission techniques often exploit large bandwidths, available to signal propagation by radio links rather than cables. The higher the bandwidth the higher the transmission capacity, a relationship that is quantitatively defined. However, frequency space, which can be regarded as another type of "natural resource," has very definite, quantitative limitations, thus setting fundamental limits to the growth of communications capacity. These limits have already been reached—from low frequencies up to radio frequencies—as evidenced by the familiar interference effects encountered in radio broadcasting. There is some room left at ultrahigh frequencies, but it is rapidly being used up. Higher frequencies, microwave and beyond, still offer considerable transmission capacities.

The choice of the most economical transmission frequency and technology depends very much on the traffic volume. Roughly speaking, as the volume increases, the trend changes from simple wires to coaxial cables to radio and microwave transmission. It is interesting that, at the same time, the materials impact of these technologies trends downward. Likewise, on a per-channel basis, various high-frequency transmission systems under development are relatively economical in their materials requirements. A buried 2-inch (5-cm) copper-lined steel pipe will carry a quarter of a million voice channels simultaneously. Microwave transmission via satellites requires materials only in the satellites and the ground stations. And optical fibers, as was discussed earlier, depend principally on inexhaustible materials.

It will be apparent that the increasing sophistication of transmission techniques depends heavily on signal processing in the central offices and terminals. The relatively less materials-intensive switching technology is substituting for transmission technology, a trend that has been given enormous impetus by the integrated circuit which is doing for switching what it is doing for calculators. And as switching and logic actions are increasingly controlled by stored programs, another form of substitution can be seen under way—that of software substituting for hardware.

Functional Opportunities for Solid State Electronics

Electronic materials, through solid state electronics, have become intimately and inextricably involved in virtually every area of technology. But weaving through the maze of applications are two broad themes that can have considerable significance for materials usage.

1) As is frequently recognized, in the primary roles of telecommunications and information handling, solid state electronics can provide alternative forms of communication. Video transmission could substitute for some personal travel, whether for employment, business, personal, educational, recreational, cultural, or other purposes. Likewise, facsimile transmission could substitute for some mail services, and credit card "readers" can be used to record and process financial transactions. "Communicating to work rather than commuting," the "wired community," and the "cashless society" are familiar phrases that convey some of the potential that electronics has for providing new services to society. Such substitutions could make positive contributions to materials conservation by lessening society's dependence on materials-intensive transportation and construction technologies (for vehicles, roads, offices, and the like).

2) Perhaps less direct but with even more potential for materials conservation overall, is the use of solid state electronics to sense, monitor, and advise on the real-time performance and reliability of equipment. For example, sensing devices coupled to microprocessors or minicomputers might provide a direct display of the fuel performance of automobile engines, information which can be used to ensure its efficient use. Sensors monitoring room occupancy could be used to control lighting and heating. Sensors that could reliably monitor structural fatigue or reveal defects could reduce the ignorance that leads to materials extravagance and overdesign in order to meet desired safety and reliability standards.

Health monitoring combines many of the features described above. Sensors attached to patients, for example, for taking blood pressure or electrocardiograms, can be used to transmit information over the telephone network to doctors (or comput-

ers) who can then interpret the signals so received and advise on appropriate actions.

These various elements of electronics technology are capable of moving us closer to the era of intelligent machines, or "robotics," in which apparatus made up of sensors, microprocessors, and servomechanisms will be able to take over many functions normally performed by humans. Some of the possibilities that can be foreseen include the following (*2*).

▶ Automated intelligence system. In concept this is a general augmenter of human intelligence, capable of automatically monitoring ongoing streams of input data, coordinating facts, and making logical inferences to obtain insights.

▶ Talking typewriter. This voice-operated typewriter would be capable of converting spoken language into typewritten form at the speed of normal speech, and with an error rate about equivalent to that of a human typist.

▶ Voice-response order taker. Capable of handling spoken questions about orders for merchandise, this system would make up orders on request, look up catalog information, and inform the user with audible messages.

▶ Automatic identification system. Using voiceprints, fingerprints, or facial matching, this system would automatically recognize individuals, performing a unique personal identification.

▶ Automatic diagnostician. Based on biological tests and on questions answered by patients, this system would interactively or automatically supply medical diagnoses.

▶ Industrial robot. Using both visual and manipulative skills, this type of robot would perform product inspection and assembly in a wide variety of automated factory working environments.

▶ Robot tutor. This would not be simple-minded programmed learning but complex interaction near the level provided by a human teacher. Given an appropriate data base, it would accept verbal and biological responses from the student and individually tailor the course of instruction.

▶ Universal game player. Capable of operating at skill levels from novice to master, this machine would play such games as chess, checkers, Kalah, Go, bridge, Scrabble, and Monopoly.

▶ Computer-controlled artificial organs. These devices would be capable of replacing human hearts, livers, lungs, and other organs, while maintaining overall balance of body function. Present-day experiments with feedback-controlled heart pacemakers, and satellite life-support systems can be viewed as first steps toward the development of such artificial organs.

Vision and Some Problems

Electronic materials have established themselves throughout man's technological fabric. They are now as ubiquitous as iron and steel. The above examples of further developments that may be within technical reach give some idea of the enormous potential of functional substitutions via electronic materials for substituting light industry for heavy industry, thereby reducing overall needs for metals, ceramics, plastics, and energy. More quantitative studies need to be made of the net materials and energy savings that would accrue from these functional substitutions, but there is evidence that they could be significant in, for example, the substitution of telecommunications for personal travel. In view of the enormous versatility of solid state electronics it is reasonable to expect that man's ingenuity will continue to find new ways to exploit its materials- and energy-saving potential throughout all technology. It might also be noted that so far, nearly all progress in information technology has been based on inorganic materials. The future may have in store expansion into organic information materials, akin to those used in the human's information handling organs—the nervous system and the brain.

Such is the vision. But there are also many problems—material resources, technical, economic, and sociological. Among the material resource aspects, one that is frequently overlooked is that although the material content of the final solid state device may be minuscule, considerable quantities of a surprisingly large variety of processing chemicals, some relatively exotic, are often needed in its manufacture. It could well turn out that the principal material constraint on the availability of electronic devices will not be the electronic material itself, but the availability of the necessary processing chemicals. Also, it should be kept in mind that the small quantities of electronic materials often represent not insignificant expenditures of energy in obtaining them.

Foremost among the technical problems is reliability, both of hardware and software. The vaster and more complex that electronic systems become, the more reliable must their individual components or subsystems be. On the hardware side this particularly implies improved understanding of the physical and chemical mechanisms of materials failure and improved nondestructive means for detecting microscopic defects. Regarding software, there is an urgent need for practical methods for characterizing and detecting program errors.

Concerning economic matters, the relative abundance of electronic materials may tend to encourage extravagance. However, practical constraints are likely to be set by capital requirements. Electronic systems are highly capital-intensive, reflecting the relatively high, value-added factors. For example, nationwide investment in computers and communications in recent years has accounted for approximately 20 percent of all new capital available. Clearly, and especially in the face of increased demands for capital by the energy sector, massive and rapid increases in investment in electronics cannot be anticipated.

The chief problems facing the full and widespread implementation of the information age are, however, not so much technical or economic, but sociological. Electronics technology is likely to be in abundant supply, little affected by materials shortages, and this could, in principle, generate extravagant demands for it up to limits set mainly by economic considerations. However, man's attitudes, both individually and collectively, can severely hamper the introduction of enormous electronic computer, communications, and control systems.

Most people are, as yet, unfamiliar with information technology, especially two-way interactive technology, although the hand calculator may prove to be one of the most successful ways of introducing the general public to it. Nevertheless, the mass learning process will probably be much slower than the pace that technological advance alone could set. This is all the more true as the technology becomes larger, more complex, and sophisticated. Some systems can become so large and complex that very few individuals can comprehend and manage them. Breaking them down into more manageable subsystems eases some of the problems but does not eliminate them; there always have to be some individuals and organizations that can understand and manage the whole assembly of interacting subsystems.

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New Materials and Composites

Recent major advances in new metals, organics, ceramics, and composite materials are surveyed.

William B. Hillig

The search for new, better, and more available materials probably dates back to the beginning of mankind. The selection by early man of the best natural materials from which to make his implements must have involved the elements of discovery, observation, comparison, need, and capability. With time, specialized needs emerged, made possible by and requiring a correspondingly wider range of materials. Synthetic materials such as glass, ceramics, and metal alloys were discovered. These materials offered advantages in terms of performance, fabricability, and appearance over natural materials. These same general forces have persisted to the present in a continuing quest for new, better materials and have led to today's materials-oriented sciences, technologies, and arts, in which vast numbers of people are employed. These workers were creating or identifying new substances (*1*) at the rate of 250,000 entries per year in 1967, and this rate is increasing by about 5 percent per year. Of necessity, this article will be highly selective and will focus on materials having actual or perceived potential or significant utility, and on which exceptional progress has been made.

First, let us consider briefly the nature of the activity leading to new materials, the associated "driving forces," and the environment in which these forces operate today. Substantial progress in materials generally originates with a provocative discovery or concept. This stage is followed by a period of expansive exploration, often with other workers rapidly joining in to define the scope and potential of the original discovery. Later, more detailed and complete information is gathered, and the often long, difficult process of practical demonstration, optimization, and conversion into a product commences. These stages can be termed (i) the original discovery, (ii) the exploration of bounds, and (iii) exploitation. The substance of this article is concerned primarily with the first two stages.

Significant discovery can come about through the scientific exploration of new classes of substances or through unsought chance observation. Examples of the latter are the discovery of polyamide polymers (for example, nylon) and crystallizable glasses; examples of the former are the high-strength crystal whiskers. In each case the original discovery was followed by the other two stages. The first two examples led to substantial industries, whereas the latter discovery has not yet been translated into a practical product.

Another path to substantial materials progress is the discovery of a phenomenon that is scientifically challenging or one that offers potential for new kinds of devices. Phenomena, such as superconductivity or laser action, are often intimately associated with particular kinds of materials. Thus, once the phenomenon has been discovered, an exploration often follows for materials which can enhance the observed effect or achieve it more conveniently. A particularly successful example of the essential interplay between materials and phenomena is the achievement in solid-state microelectronics of almost inconceivably fine-scale and complex material structures of highly specified compositions. These devices have had a pronounced qualitative effect on modern society.

An increasingly better traveled path in the search for new materials results from the pressures to satisfy extremely important functions for which existing materials are only marginally successful, if not totally inadequate. For example, the aerospace accomplishments of recent years depended on the development of new materials and structures with high strength and high stiffness-to-weight ratios. This effort has stimulated work on low-density, high-performance composites reinforced with B and graphite fibers. More recently, the changing fuel supply situation is placing new emphasis on metals and ceramics having higher temperature capabilities for use in heat engines. These materials are needed to achieve greater Carnot efficiency and to withstand the increasingly hostile chemical environments due to the expected deterioration in the quality of economically affordable fuels.

The above paths are not mutually exclusive but rather serve to define the approaches taken by particular individuals or organizations. With the passing of the recent "golden age" of scientific support for exploratory materials research in the period from 1950 through 1970, increasing emphasis has been placed on the search for materials that meet specific "hardware" requirements. Economics and good design dictate that materials be used as efficiently as possible. Thus, materials are being worked increasingly hard. This hard working of materials can be done when the use conditions for the materials are carefully defined and controlled. However, it can also lead to problems when the same apparatus is operated under a new set of conditions. We are becoming increasingly skilled in learning to use scarce and expensive materials locally only where needed. The substitution of one class of materials for another and the reexamination of designs in terms of their functional requirements place a continuing challenge on the materials and design communities to establish better mutual realistic awareness of their respective capabilities and limitations.

The drive toward working materials increasingly hard implies an increase of materials research and development activities on near-term materials improvement and problem-solving, relative to the more speculative, high-risk exploratory materials work. This trend also suggests that locally tailorable materials systems and hybrid materials will become increasingly important, as will composites which can result in new combinations of properties not available in single homogeneous materials. Examples are claddings for high-temperature turbine alloys and fiber-reinforced composites.

In identifying "new" materials or materials advances for citation, I was unable to arrive at a very precise definition of what constitutes newness, except perhaps a judgment that the impact on society or the technical community has not yet crested. Another concern was how to organize the selected new materials. One approach could be in terms of the paths by which they emerged, as just discussed. A second approach could be to group them according to their applications, such as structural, optical, electromagnetic device materials or the like. Another scheme might be to

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classify them according to the nature of their newness, that is, new substances, new molecular or crystalline structures, or discontinuous advances in existing materials. However, materials can be grouped in a more natural way if they are classified as (i) polymers, (ii) metals, (iii) ceramics and inorganic materials, or (iv) composite materials. This is the plan I have followed below. New filamentary materials useful for composites are discussed under the composite materials heading.

New Polymeric and Organic Materials

Work in this important class of materials is presently concentrated in the exploitation and optimization stages. There has been major preoccupation with feedstock costs and availability as a result of the changing situation with respect to petroleum and natural gas supplies. Increasing emphasis on safety and consumer issues has resulted in increased industry efforts and predictable progress in reducing flame and smoke hazards, mainly through the use of additives. A relatively new emerging family (*2*) of polymers that may offer particular advantages in this regard are the polyorganophosphazenes. These polymers have a -(PN)- inorganic backbone; the specific characteristics are conferred by the organic side groups. By analogy with the silicones, this family of polymers can form rubbers that remain flexible to very low temperatures. These polymers have good hydrolytic stability and oxidation resistance but are somewhat difficult to synthesize. They have been described (*2*) as being at the state of development at which silicones were in the early 1950's.

A strong driving force for new polymer work is based on the fact that these materials can compete successfully against metals, especially in areas where low-temperature nonferrous die castings have been used. There is opportunity for widely expanded use in high-volume applications, such as appliances and automobiles. Their use in engine compartment components depends on solving the problems of creep (deformation with time under load), chemical stability at temperatures above 100°C, and resistance to petroleum solvents. In many such applications, the ability to fill space economically is an important consideration. Hence, structural foams (*3*) are a new, emerging material form in which voids are purposely introduced into the structural polymer at typical concentrations of 10 to 50 percent. Foams such as shown in Fig. 1 can also be introduced to achieve greater rigidity and creep resistance.

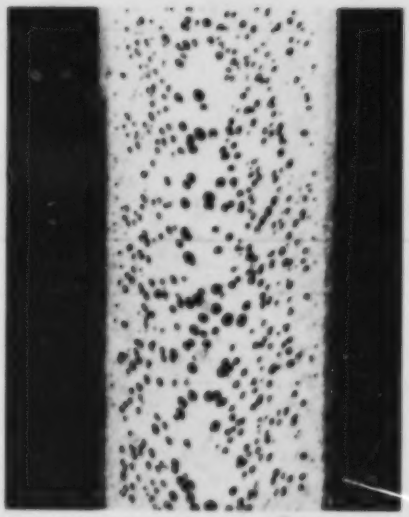

Fig. 1. Foamed polycarbonate resin. Introduction of about 20 percent voids increases the flexural stiffness on an equal weight basis by a factor of 2.

There are many other critical engineering applications, such as in aircraft, not ideally met by other materials, in which temperature capabilities of 300°C or more are desired. Hence, substantial efforts are being made to develop high-temperature thermoplastics (materials that soften upon heating), such as polysulfones and polyimides, as well as high-temperature thermosets (materials that remain rigid when heated), based on heterocyclic systems, such as the benzimidizoles and quinoxalines.

Other materials which may develop significant practical importance are certain electrically active compounds, which have been described (*4*) as having metal-like properties. The salts of tetracyanoquinodimethane (TCNQ) exhibit electronic conductivities equal to about 1 percent of that of graphite at room temperature. This conductivity is strongly anisotropic and increases with decreasing temperature until a metal-insulator transition occurs, below which the material no longer conducts. However, a TCNQ salt has recently been discovered that retains metal-like conductivity at near 0°K. A second material, $(SN)_x$, an inorganic polymer, has been found to exhibit superconductivity at temperatures below 0.3°K. This work has been confirmed by repeated measurements. This bronze, shiny material exhibits appreciable electronic conductivity above 0.3°K and becomes superconducting in spite of the fact that it possesses considerable disorder, and it offers the hope (*5*) that improvements are possible. Piezoelectric behavior has recently been reported (*6*) in polyvinylide fluoride, polyvinyl fluoride, and certain other polymers. These are highly orientable, readily crystallizable polymers containing dipolar chain elements, and they have sensitivities nearly equal to those of the semiconductor counterparts. The polymers can be made into piezoelectric films in which the dipoles are aligned by first a stretching of the films to produce a highly oriented structure and then a polarization through the application of large electric fields. These polymers can be used as strain sensors, acoustic transducers in microphones, and loudspeakers. Other advances in polymeric systems are discussed in the sections dealing with composites.

New Metallic Materials

Because metals are a mature class of materials, the opportunities for the discovery of new substances or structures might seem to be relatively remote. Nevertheless, there have been noteworthy discoveries in the categories of new substances, new structures, old materials in which quantum advances have been made, and known materials having newly discovered properties.

Since the discovery of superconductivity in 1911, a search has been under way (*7*) for practical materials that retain this behavior to as high a critical temperature T_c as possible, especially for materials that could operate at liquid hydrogen temperature, 20°K. Two alloys, V_3Si and Nb_3Sn, which have the A-15 (β-tungsten) structure, were discovered in 1953 and 1954 to have T_c values of 17.1° and 18°K, respectively. Interestingly, it took 13 years of further intensive search to reach the milestone goal of a T_c value of 20°K with $Nb_3Al_{0.8}Ge_{0.2}$, and this achievement was then surpassed in 1973 and 1974 by Nb_3Ga and Nb_3Ge, all A-15 materials. The latter alloy has a T_c of 23.2°K, the present record. This search is hampered by the lack of an adequate theory which connects composition to T_c. It remains to be seen whether these materials can now make practical the potential of superconductivity for such uses as electric power transmission lines, and new high-energy density motors, generators, and the like.

The so-called glassy or amorphous metals have been receiving accelerated attention since their discovery (*8*) in 1960. Since then, numerous noncrystalline alloys have been identified (*9*) and have been formed into continuous ribbon and wire. Cooling rates of about 10^6 degrees per second or more are required to produce amorphous metals. The most favorable compositions are those which correspond to eutectics with particularly low melting points and which contain transition elements, such as Ni, Pd, Zr, and La, as well as metalloids, such as B, C, P, and Si. Discernible order-

ing in the metal glasses extends only a few atom distances as is the case for conventional oxide glasses. These glasses have Young's moduli about 30 percent less than that of the crystalline state and high ultimate strengths that rival those of conventional glass fibers. In contrast to conventional glasses, they show marked ductility, as much as 50 percent strain under bending; consequently, they are much less notch-sensitive. Their densities are nearly equal to the crystalline state values. These behaviors imply that the binding forces remain essentially centrosymmetric. Toughness in the metal glasses, as measured by the crack extension force, is almost an order of magnitude greater than for their crystalline counterparts. These properties, along with interesting magnetic behavior and the good galvanic corrosion resistance (*10*) of some compositions, have generated considerable interest and speculation about the place of glassy metals in materials technology.

The oriented eutectics (*11*), often called "in situ composites," are a relatively new class of metal structures that offer great potential for increasing the temperature capability of high-strength alloys. Such materials are needed to increase the efficiency performance of gas and aircraft turbines. Intermetallic compounds are known that have good high-temperature properties, but they tend to be brittle and difficult to fabricate. However, in favorable cases such intermetallics can be cast into useful shapes by the controlled solidification of eutectic alloy compositions. Plates or rods of strong intermetallic phases form as dispersions with a second continuous or lamellar phase. The compositions and proportions of the phases are fixed by phase equilibria constraints, and the fineness of the structure is adjustable by control of the growth conditions. The Ni_3Al and Ni_3Nb (*12*) and the TaC-containing (*13*) systems shown in Fig. 2 have shown particular promise for use as new turbine materials. The first material is a lamellar structure; in the second family of materials, the TaC is present as rods in a continuous matrix of Ni, Co, or other more complex compositions. Both systems have been produced in the form of turbine blades and appear to offer a quantum advance over the best earlier alloys. Oriented eutectic structures are not limited to all-metal systems.

An important discontinuous advance has occurred in a well-known commodity material, namely, silicon iron, used for transformer cores. Annual electric losses in the United States attributable to distribution transformer core loss are estimated to be about 3×10^{10} kilowatt-hours, that is, the electrical energy needed per year to supply about 3 million households. Silicon

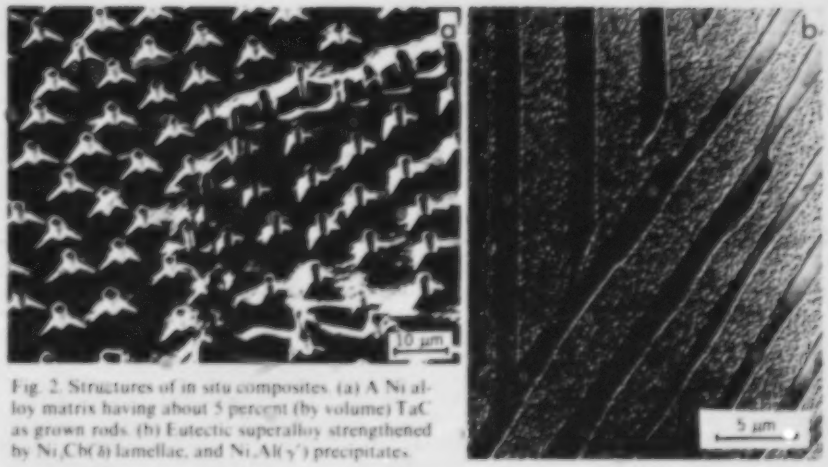

Fig. 2. Structures of in situ composites. (a) A Ni alloy matrix having about 5 percent (by volume) TaC as grown rods. (b) Eutectic superalloy strengthened by $Ni_3Cb(\delta)$ lamellae, and $Ni_3Al(\gamma')$ precipitates.

iron ideally requires a "cube-on-edge" texture for best properties. A good approximation to this texture is achieved by a complex process of rolling and annealing in which MnS is used as a grain growth inhibitor during certain critical steps. A breakthrough came about in Japan (*14*) where a new commercial process was developed in which two inhibitors, AlN plus MnS, were used to control grain growth. Not only was the texture improved, but a surface coating (*15*) was found to be effective with silicon iron for further reducing losses through an advantageous magnetostrictive mechanism.

An obstacle to the development of commercial fast breeder reactors was the unexpected swelling (*16*) of the stainless steels, considered as fuel-cladding materials, which occurred under irradiation with fast neutrons at reactor temperatures. As much as 7 percent swelling occurred when the neutron fluence had reached only 25 percent of the level needed for commercial operation. Some alloys swelled as much as 100 percent when subjected to a simulation of the full target fluence level. Internal voids cause the swelling. These voids result from the slight imbalance in favor of interstitial atom capture relative to vacant atom site capture at sinks such as dislocations. The excess vacancies then collect to form voids. The vacancies and interstitials are produced by the fast neutron collision processes. As shown (*17*) in Fig. 3, the propensity for such swelling varies by three orders of magnitude in the simple Fe-Ni-Cr alloy system. Certain trace alloying elements, such as Si, Ti, Zr, and Nb, also reduce swelling (*18*). The composition of the cladding steel initially selected was subsequently shown to lie in a high swelling region. If corrosion and other requirements can be satisfied, a satisfactory solution appears to be at hand for this particular problem of the fast breeder reactor.

Ceramic and Inorganic Materials

Advances in new ceramics have resulted, largely but not entirely, from the control of microstructure and purity. This accomplishment has required major advances in processing. For example, an old material for which an important new use has emerged is sodium β-alumina. This material has the nominal composition $Na_2O \cdot 11Al_2O_3$ and consists of NaO planes sandwiched between spinel blocks. It

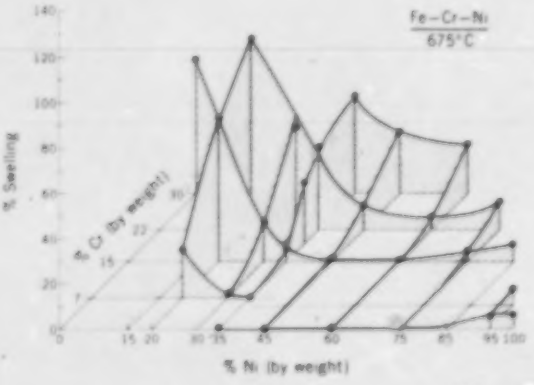

Fig. 3. Dependence of fast neutron induced swelling in Fe-Ni-Cr alloy on the Cr and Ni contents.

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Table 1. Physical properties of reinforcing fibers relative to stainless steel.

Material	Relative density	Equal volume basis		Equal weight basis	
		Tensile strength	Stiffness	Tensile strength	Stiffness
304 stainless steel	1	1	1	1	1
Glass metal, 34Ni/29Fe/15Cr/22(P + B)	0.9*	1.2	0.7	1.3	0.8
S-glass	0.31	1.7	0.45	5.5	1.45
Boron (W-core)	0.31	1.7	2	5.5	6.5
Graphite	0.22	1.1–1.4	1–2	5–6.4	4.5–9
Kevlar-49 Aramid	0.18	1.3	0.7	7.2	3.9

*Estimated value

has long been used as a lining for the huge tanks used to hold molten glass for manufacturing. In 1966 it was noted (*19*) that this material has a remarkably high ionic conductivity, which at 350°C exceeds that of saturated brine (at room temperature). The compound β-alumina is the most useful of a class of materials (*20*) known as superionic conductors and has particular importance for high-energy battery systems, such as sodium-sulfur cells, or for fuel cell applications. It can be used not only as a nonaqueous electrolyte but also as a structural element. It has electrical properties that depend on the crystalline microstructure (*21*) as well as on the presence of dopants. However, it is difficult to sinter, especially to the desired microstructure. In most applications impermeable structures are required. Sound, good-performing material has been made. Because of the difficulty of satisfying all of the necessary conditions, work on β-alumina and its structural variant β''-alumina is the continuing subject of intensive work in many laboratories.

The achievement of higher-efficiency thermomechanical engines requires the availability of high-temperature, high-performance structural materials. The compounds SiC, Si_3N_4, and more recently Al_2O_3–Si_3N_4 alloys have received particular attention (*22*) for such applications because of their good strength and good corrosion and thermal shock resistance. Nonionic ceramics, such as SiC and Si_3N_4, have been difficult to fabricate by standard methods. In these materials, as in many other ceramics, the making of the material is inseparable from the making of the component.

The compound Si_3N_4 can be made directly from the elements with excellent shape fidelity. However, this lengthy process results in material that contains about 20 percent voids but, nevertheless, has strengths up to 50,000 pounds per square inch (14.7 pounds per square inch = 1 atmosphere). Dense Si_3N_4 can be made by hot-pressing the powder with small amounts of MgO used as a sintering aid. The hot-pressed material is about three times as strong as the reaction-sintered material and, for a ceramic, is relatively tough. However, only approximate shapes can be made, and this material exhibits creep at elevated temperatures. The replacement of MgO by Y_2O_3 appears to be beneficial (*23*) in ameliorating the creep problem.

The situation with SiC is somewhat analogous in that both reaction-bonded and hot-pressed grades are now commercially available. The former results from mixing SiC with graphite, shaping, and then reacting with molten Si, and produces a fully dense material with a strength of about 75,000 pounds per square inch. Hot-pressed SiC can also be made to approximate shapes with reported strengths somewhat less than for the corresponding Si_3N_4 material. The creep properties depend on aids used to promote consolidation during hot-pressing. The use of W and Al_2O_3 results in substantially higher creep rates than when B is used. A major recent scientific and technical advance (*24*) was the discovery that SiC can be conventionally sintered at 2100°C by standard ceramic techniques through the addition of small amounts of B and C. This procedure makes possible the production of complex shapes. The resulting properties are comparable to those of the hot-pressed material and, in addition, the SiC exhibits greater creep resistance.

SiAlON's, which are alloys of Al_2O_3 and Si_3N_4, are possible candidates as high-temperature structural materials. The phase equilibria relations in this quaternary system are complex and may account for various conflicting reports regarding the merits of SiAlON's. This system offers some promise of easier fabrication. However, much more work is needed to determine its ultimate importance.

The ability to form polycrystalline dense compacts (*25*) of diamonds and cubic BN is another notable achievement in the area of refractory nonionic solids. Even though these substances are the hardest known materials, single crystals exhibit marked anisotropy in their hardness and strength. As a result, cleavage fracture can occur. Hence, for cutting tools to be used in rock drilling, metal cutting, or wire dies, it is advantageous to have all crystal faces exposed to provide uniform wear and resistance to extended crack propagation. The synthesis of these compacts, therefore, has great significance for increasing productivity in areas of increasing economic importance.

Finally, among the inorganic glasses, the achievement of ultraclear glass fibers (*26*) in which the optical transmission loss is as little as 1 decibel per kilometer is a remarkable accomplishment. This achievement was made possible by an extremely careful synthesis process in which all traces of deleterious impurities are held to concentrations in the range of parts per billion. Such glass fibers are needed as optical wave guides if the promise of lasers in communications is to be realized. A second area of new materials advance in glasses results from the rapidly expanding interest in the so-called "chalcogenide" glasses (*27*).

This interest stems from such properties as bistable electrical switching behavior, light-induced nucleation, strain-induced nucleation, as well as other unusual structure- and transport-related characteristics. In a sense, these glasses are the complements of the metallic glasses. They consist mainly of combinations of the nonmetals and metalloids, such as As, Ge, S, Se, Si, and Te, but they may also contain appreciable concentrations of such metals as Ag, Cd, Cu, and Tl. These glasses continue to be a fruitful area of research for experimental and theoretical scientists and, in addition, offer many device possibilities as nonlinear elements and memories. However, it remains to be seen what their technological importance will be in the competition with other electrical and photoactive materials.

New Composite Materials

Composites are heterogeneous materials systems in which several substances are combined into a coherent structure. Many common materials, not usually classed as composites, are nevertheless heterogeneous structures, for example, carbon-filled rubber, ABS plastic, carbon steel, superalloys, porcelain, and ruby glass. However, in contrast to the case for composites, the proportions, size, and shape of the various phases in these heterogeneous structures are often determined indirectly through such factors as solubility, nucleation, and growth kinetics. The in situ composites cited above are examples of an intermediate class of composite for which great care is taken to produce a desired

heterogeneous structure; however, in the case of fiber glass epoxy composites, the fiber choice, arrangement, and proportions are independently controlled by the fabricator. Such control or tailorability contributes to the importance of composites. In the discussion that follows, I have found it useful to distinguish between structural and functional composites. The former are used mainly for their mechanical properties and the latter for their special electrical, chemical, or other characteristics.

Structural composites. The search for materials having exceptional strength and stiffness, and useful over a wide range of conditions, has stimulated wide activity in the search for new reinforcing fibers. For rotating components or for air- or space-borne components, high mechanical performance at low density is important. The standard high-performance fiber of longest standing is E-glass. However, usage of the stronger and stiffer S-glass is increasing. Although these fibers are strong, they lack the stiffness needed for many applications. Another common filament is high-strength steel wire, which is strong and stiff but has a relatively high density. Steel and glass are the commodity filamentary materials against which the more advanced fibers can be compared.

Vapor-deposited B on a W- or C-core has been available for more than a decade. This fiber has the strength and density of glass but twice the stiffness of steel. However, its high cost of about $180 per pound ($0.40 per gram) limits the use of this reliable fiber material to special applications. This price is estimated to drop by about a third if sufficient volume develops. Carbon fiber is actually a family of fibers available over a range of strengths and stiffnesses. These properties plus density are functions of the starting material and processing conditions. Carbon fiber is produced by pyrolyzing and subsequently further heat-treating textile or pitch fibers. Carbon fiber has a typical diameter of 8 μm, whereas that of the B fibers ranges from 100 to 200 μm. Thus, the B fibers are usually handled as monofilaments, whereas the C fibers are gathered in bundles of 1000 or more individual fibers. The cost of continuous high-strength C fiber is currently about $60 per pound, and it is projected that the price will drop to about $10 per pound.

Recently a quantum advance was achieved in the mechanical properties of polymer fibers. Although it was recognized (*28*) that the C–C bond is intrinsically stiff in stretching, the tetrahedral C–C–C bonding in polymers results in a "coiled spring" structure. Hence, uncoiling and flexing rather than stretching account for the ordinarily observed low modulus of organic polymers. A high-modulus polymeric fiber (*29*) has been produced that is 50 percent stiffer than S-glass, comparable in strength, but less dense. The polymer is poly-aromatic-amide (aramide) in which geometric factors in the molecular structure prevent coiling. This fiber has the interesting, unusual characteristic of behaving like a chain; that is, it is strong in tension but weak in compression. This fiber is produced by spinning from a liquid crystal solution. Because of the close kinship between this process and the spinning of conventional textile fibers, lower cost can be anticipated for this material when it reaches high production volumes than would be expected for B or graphite. The current price is $3.50 to $8.50 per pound. Forms having Young's moduli of 19×10^6 and 9×10^6 pounds per square inch are available. The latter form is finding use as tire cord.

Fig. 4. Experimental aircraft engine fan blade made of graphite fiber-epoxy composite. The light-colored metal strip on the one edge protects the blade should birds accidentally enter the engine. The blade is about 60 centimeters long.

A recent laboratory achievement (*30*) has been the production of polyethylene with a strength and stiffness comparable to that of E-glass. Instead of the usual spherulitic crystallite structure, these fibers consist of parallel crystalline polymer fibrils which result from extrusion under very high pressure (2500 atmospheres) at 134°C. A one-component composite consisting of these fibers embedded in a matrix of normal polyethylene has been given preliminary study.

Table 1 shows a comparisoc of the properties of the various fibers relative to type 304 stainless steel wire, which has a characteristic strength of 300,000 pounds per square inch and a Young's modulus of 27×10^6 pounds per square inch. Because strengths can depend on the time at stress and on the number of loading and unloading cycles, the rankings can vary significantly depending on how the material will be used.

Advances in the making of oxide fibers have been substantial. There are several ingenious methods for producing continuous single crystals of oxides and other materials as well with a range of cross sections, shapes, and sizes. One method (*31*) is based on solidification from the melt with the use of a special shape-defining orifice. A second method is a controlled floating zone technique (*32*) in which laser heating is used. Very fine, continuous polycrystalline fibers (*33*) of Al_2O_3, ZrO_2, and mixed oxide compositions have also been achieved. Although their strengths are less than those of the other fibers cited, these fibers are relatively inexpensive and appear to offer the potential for high-temperature use. The polycrystalline materials are being used as catalyst supports and high-temperature insulation.

A wide variety of composites (*34*) have been made with the use of the above-mentioned fibers. Glass, B, graphite, and the aramide fibers have been used variously to reinforce epoxy, polyester, polyimide, and other resins. Materials with outstanding strength, toughness, and stiffness can be produced. Failure in these materials is often more benign than for the monolithic materials. Thus, composites find use in pressure vessels, aircraft, high-specific-energy flywheels, textile equipment, and sporting goods. An example is shown in Fig. 4. The weight savings and good mechanical properties suggest that these materials will find increasing use in automobiles as their costs for a given function become competitive with those of steel. The polymer matrix composites can be characterized as (i) being convenient to fabricate, (ii) having high strength parallel to the fibers, (iii) being weak transverse to the fibers, (iv) having low density, and (v) having a useful upper temperature of 100° to 300°C depending on the resin.

Certain of these limitations can be overcome by the use of metal matrices such as Al or Ti. Among the benefits that derive from the use of these matrices are better transverse properties and higher temper-

14C

ature capability. However, these materials are more dense and more difficult to fabricate. Boron and steel and, more recently, graphite, SiC, and Al_2O_3 filaments in combination with Al alloys are among the most successful metal matrix composites. These materials are being considered for such applications as turbine compressor blades and aircraft skins. However, degradation of properties due to reaction between the matrix and the fibers is a basic problem, especially in very-high-temperature systems.

This degradation has frustrated most attempts to produce very-high-temperature composites. The use of refractory metal filaments to reinforce superalloys and Si_3N_4 has had some success, the main disadvantages being high density and limited fabricability, respectively. However, an approach that results in a readily fabricable, temperature-stable, fully dense material, useful to 1370°C or perhaps more, is the Si-SiC composite (*35*). This material is somewhat analogous to the in situ composites in that the microstructure is the end product of a high-temperature reaction; the C fibers are converted to SiC upon infiltration with molten Si. This composite can be precision-formed into a wide range of complex shapes. Its mechanical properties are tailorable to a considerable degree. It can be produced so as to exhibit limited ductility at elevated temperatures. Its strength behavior is somewhat similar to that of reaction-bonded SiC. This composite material is expected to find use in high-temperature and corrosive environment applications, such as in gas turbines.

An important and rapidly growing class of composites is the reinforced thermoplastics (*36*). Typically these composites consist of a random mixture of oriented chopped glass fibers combined with an injection-moldable polymer, such as polypropylene, polycarbonate, or the like. The result is a material that has markedly improved dimensional stability, an extended temperature range, and improved strength by comparison with that of the base resin, while retaining ease of manufacture and low cost. One of the advantages over the corresponding reinforced thermosets is the shorter forming times needed to produce shapes, since only heatup and cooling are involved. Another advantage is that it is possible to rework material, thus cutting down on scrap. The use of reinforced thermoplastics is growing at the astonishing rate of 27 percent per year. These materials are used for a wide variety of general purpose applications, such as automotive and appliance components.

Functional composites. These composites exhibit special chemical, electrical, and optical characteristics resulting from special materials combinations and configurations. For example, high degrees of separation from a mixture of gases can be achieved by selective permeation (*37*) through immobilized liquid membranes. These membranes function via reversible chemical reactions that can occur in the solutions contained within them. The separation of CO_2 from air in the ratio of 1500 : 1 is made possible by the use of HCO_3^- / CO_3^{2-} buffer solution supported within porous polymeric films to produce the membrane structure. By comparison a film of silicone rubber, a highly permeable but chemically passive material, exhibits a CO_2/O_2 separation of 5. Other gases, such as H_2S, SO_2, and N_2, which when dissolved can ionize or complex, can also be selectively separated by appropriate choice of the active liquid material. Such membrane structures and the principles outlined offer promise for dealing with the increasing environmental problems of fuel and combustion gas cleanup.

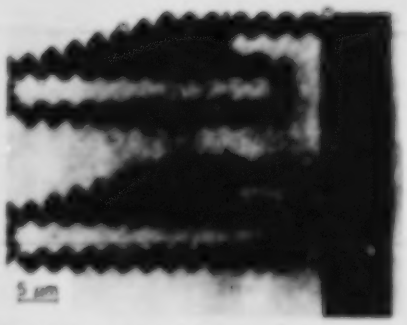

Fig. 5. Patterns formed in permalloy by the use of x-ray lithography. The spacing between chevrons is 0.2 μm.

Substantial advances (*38*) have also been achieved in passive functional composites. These materials consist of claddings and laminations, among other things. Such coatings applied to high-temperature metals by evaporation and plasma spraying have been very effective in further increasing the temperature capability and corrosion resistance of high-temperature alloys. Aluminides, chromides, and even precious metals are used to protect turbine blades and chemical process equipment.

Laminated metals (*39*) have been developed in which as many as five or six alloy materials can be placed in furrows in a base metal ribbon. Thus, thin strips of Au, Cu, and Sn alloys can be embedded in the surface of a steel strip to provide good electrical contacts, soldering capability, and good mechanical strength. Furthermore, such structures can greatly minimize the need for costly or scarce materials.

The extremely fine control and complex heterogeneous structure of advanced solid-state devices represents a state of the art of structural and compositional control of composite material systems on a scale incomprehensible less than a generation ago. Very uniform P-doping of Si base structures has been produced by neutron irradiation of the Si to produce the P by isotope transmutation (*40*). With the new techniques of ion implantation (*41*) and x-ray lithography (*42*), the latter shown in Fig. 5, it is possible to produce extremely sharply delineated junction regions and structure on a scale smaller than the wavelength of light. The result of such advances is an array of electronic multifunctional devices of greater complexity compressed into smaller structures and higher performance in terms of the switching times and frequency capabilities. For example, defect-free sensors (*43*) have been constructed, with the use of Si integrated circuit technology, which over an area of about 1 square centimeter have 244 lines of 248 elements—over 62,000 individual sites, each of which is interrogated as to the light level to which it is exposed. Such sensors closely approach the goal of a TV camera on a chip.

Conclusions

The numerous examples cited here offer ample evidence that great ingenuity is being used in providing new materials to meet current problems. There have been relatively few truly new materials, in the sense of materials that were not known before. However, substantial improvements in all classes of materials are readily identifiable. Although the details of such advances may not have been predictable, it is no surprise that substantial improvement could result from the application of talent to today's pressing problems. What is of more concern is the fact that there is not more advanced materials research and development being directed at major basic materials phenomena.

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Brittle Ceramic Materials for High Temperature Structures

Arthur L. Robinson

Two of the world's most pressing problems—the increasing cost and decreasing availability of fossil fuels and the pollution of the environment resulting from their use—could be partially solved if the operating temperature of a heat engine were raised. More useful work for the same amount of fuel consumed would be obtained because of the engine's increased thermal efficiency, and fewer pollution-causing emissions would be released because of the more complete combustion permitted by richer fuel to air ratios.

Unfortunately, even the most exotic high temperature alloys (super alloys containing large amounts of nickel, cobalt, or chromium) cannot withstand temperatures in excess of about 1100°C. However, as a result of advances made over the past 15 years, refractory ceramic materials based on silicon nitride (Si_3N_4) and silicon carbide (SiC) are being considered for use as high temperature structural materials in places where previously only metals would have been used. Most current research is oriented toward ceramic gas turbines for vehicles, stationary power generators, and remotely piloted aircraft.

As compared with metals, ceramics are more resistant to high temperatures, oxidation, corrosion, and erosion, and are quite strong, but they are quite brittle. In particular, when rapid temperature changes occur, ceramics tend to fracture under the resulting thermal stresses, a condition known as thermal shock. Moreover, the virtual absence of plastic deformation that can relieve stress concentrations in brittle materials means that the stresses must be accurately known everywhere in a part, so that design is a formidable problem. As a result, interest in ceramics as structural materials has been a cyclical phenomenon since about 1900.

Interest in silicon carbide and silicon nitride derives from their having a combination of moderate-to-low linear thermal expansion coefficients and high-to-moderate thermal conductivities, respectively. These ceramics are thus less susceptible to thermal shock than other such materials. But because both compounds decompose by sublimation at high temperatures, parts cannot be fabricated by casting, thus necessitating recourse to powder metallurgical methods, such as sintering or hot-pressing.

In the mid-1950's, workers at the Admiralty Materials Laboratory in the United Kingdom discovered that relatively dense silicon nitride with good properties could be made by reacting silicon powder in a nitrogen atmosphere at high temperature. The first step in this so-called reaction bonding or reaction sintering process is the compacting of the silicon powder into the desired shape. An organic binder or plasticizing agent (which is later burned off) is mixed with the silicon powder to hold it together and to permit the formation of complex shapes through the use of processes such as injection molding, which is common in the plastics industry. This "green" body is heated first to 1350°C and then to 1450°C to bring about the nitridation reaction.

Silicon nitride parts made in this way are about 70 to 85 percent of the maximum possible density and maintain their mechanical strength up to about 1400°C. Pores larger than 10 micrometers seem to act as flaws which can serve as the origin of cracks that lead to fracture.

A somewhat similar process has since been developed for silicon carbide by researchers at the Atomic Energy Authority laboratory at Springfield in the United Kingdom. A mixture of silicon carbide powder and carbon powder is formed compactly to the desired shape. An organic binder may or may not be used. The compacted powder is heated to 1600°C to 1700°C, and molten silicon metal is allowed to infiltrate the powder. The silicon and carbon react to form silicon carbide, which binds the powder particles together.

Silicon carbide made in this manner can reach 100 percent of the theoretical den-

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sity, but with the disadvantage that some unreacted silicon remains. The silicon melts at about 1410°C thus limiting the use of reaction bonded silicon carbide to temperatures much lower than this.

In the meantime, at the end of the 1950's, workers at The Plessey Company, Ltd., also in the United Kingdom, found that adding small amounts of magnesia (MgO) permitted dense silicon nitride to be made by hot-pressing. Hot-pressing involves simultaneous application of uniaxial pressure (250 atmospheres) and heat (1700°C).

Use of magnesia (about 5 percent by weight) for hot-pressed silicon nitride was further improved by the British company Joseph Lucas Ltd.; by 1970 theirs was the standard way to produce this material. Improvements by the Lucas company basically involved obtaining small grain sizes (the ceramic is crystalline, with the size of the crystalline regions being of the order of 1 micrometer) with a resulting low porosity and high strength.

Hot-pressed silicon nitride has mechanical properties that are superior to those of the reaction bonded material at room temperature. For example, the bending strength is about three times higher. Above about 1200°C, however, the properties degrade. One problem is the onset of creep. Creep is the plastic deformation of a material under a load lower than that normally required to cause the material to fail and can cause significant dimensional charges in parts. A decrease in strength also occurs at high temperatures and may be attributable to the existence of small cracks that grow slowly before reaching a large enough size for fracture to occur.

Work at several laboratories has resulted in a model that ascribes the degradation of mechanical strength at high temperatures to the formation, during hot-pressing, of a glassy magnesium silicate (Mg_2SiO_4) phase between the particles of silicon nitride. This glassy grain boundary phase is thought to soften at elevated temperatures so that the grains can slide past one another, giving rise both to the creep phenomenon and the slow crack growth. The model is still regarded as controversial.

A hot-pressed version of silicon carbide has also been developed with alumina (Al_2O_3) as the densification aid. Hot-pressed silicon carbide is similarly afflicted with a putative vitreous grain boundary phase that limits its service to temperatures below about 1200°C to 1400°C. However, as compared with the silicon nitride, silicon carbide is considerably less susceptible to creep, the rate of creep being 10^3 to 10^4 times lower.

A Peculiar Fibrous Microstructure

Hot-pressed silicon nitride is considerably tougher than silicon carbide. Toughness is different from strength and relates to the resistance to catastrophic crack growth (fracture) under an applied load. According to F. F. Lange of the Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, the toughness of silicon nitride is likely due to its peculiar fibrous microstructure. Silicon carbide consists of more symmetrical grains. This explanation awaits quantitative verification, however, and is not universally accepted by other investigators.

Hot-pressed ceramics and reaction bonded versions actually represent complementary materials. Although the hot-pressed material is denser and stronger than the reaction bonded, hot-pressing is limited to fabricating simple shapes. Moreover, there is considerable shrinkage (at least 50 percent by volume) during hot-pressing. Both considerations result in the need for expensive diamond grinding to bring the hot-pressed parts into final shape. Reaction bonded ceramics, however, can be fabricated into complex shapes relatively inexpensively.

In the last 4 years, a number of improvements in the properties of silicon nitride and silicon carbide have been made. Lange and his co-workers discovered, for example, that impurities play an especially important role in the high temperature properties of hot-pressed ceramics, apparently by affecting the viscosity of the glassy grain boundary silicate phase. Calcium is the worst offender, having deleterious effects at concentrations as low as a few hundred parts per million. Commercial vendors of silicon nitride and silicon carbide now market powders of high purity.

Although hot-pressed silicon nitride made from high purity powder exhibits increased resistance to creep at high temperatures, the properties of the magnesium silicate glass still limit the performance. George Gazza of the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts, thus began looking for better densification additives than magnesia. After an extensive search, Gazza decided to try yttria (Y_2O_3) because yttrium silicate ought to be more refractory than magnesium silicate.

As it turned out, additions of 10 to 20 percent (by weight) of yttria to silicon nitride powder were found to increase the creep resistance of hot-pressed silicon nitride about 1000 times to nearly that of hot-pressed silicon carbide at 1400°C. Some researchers now think that the mechanism for enhanced high temperature properties is related to the formation of a crystalline yttrium oxynitride phase (or phases) that result when the yttria and the silicon nitride react. Moreover, researchers have found that calcium may not be as detrimental to the properties of hot-pressed silicon nitride when yttria is added.

Roy Rice and his associates at the Naval Research Laboratory have tried using zirconia (ZrO_2) as a densification aid and found more modest beneficial effects on the high temperature properties of silicon nitride. For example, scientists at the Avco Corporation, Lowell, Massachusetts, and the Aerospace Research Laboratories, Wright-Patterson Air Force Base, Ohio, made measurements indicating that the stress-rupture properties and oxidation resistance increased tenfold.

Sintering is similar to hot-pressing in that high temperatures are used to bring about densification of a powder body and binding of the particles together, but it is unlike hot-pressing in that no pressure is applied during the heat treatment. Sintering has not been successfully applied to the making of dense silicon carbide or silicon nitride until recently.

Svante Prochazka of the General Electric Research and Development Center, Schenectady, New York, has found that additions of less than 1 percent (by weight) of boron and carbon to silicon carbide powder can permit the sintering of dense silicon carbide parts. Although the boron apparently does segregate at the grain boundaries, there is no glassy grain boundary phase. As a result, the high temperature strength of the General Electric silicon carbide is retained up to 1600°C, and creep is undetectable at 1480°C. Although there is some shrinkage during the sintering process, the expensive diamond grinding required for hot-pressed ceramics can be avoided.

Silicon nitride can be sintered to nearly full density as well, if about 50 percent (by weight) alumina is "added" as a sintering aid. The resulting ceramic is actually a family of solid solutions of silicon nitride and alumina and has been given the name "sialon" (Si-Al-O-N). The properties of these ceramics have been studied by K. H. Jack and his colleagues at the University of Newcastle upon Tyne in the United Kingdom and by Y. Oyama and his associates at the Toyota Research Laboratories in Japan, as well as in the several laboratories in the United States. The motivation for their study is to be able to combine the desirable properties of hot-pressed silicon nitride with the inexpensiveness and ease of fabrication possible with the sintering process. Despite much enthusiasm early on, no sialons have yet been made

with properties comparable to good hot-pressed silicon nitride.

The beneficial aspects of these advances do not, as a rule, change the intrinsically brittle nature of ceramics, nor do they increase the impact strength or fracture toughness. There have, however, been a number of approaches to ameliorating the susceptibility of silicon nitride and especially silicon carbide to fracture.

Since many of the cracks (actually microcracks many of which have the dimensions of the order of micrometers) are on the surface of the ceramic part, Henry Kirchner and his co-workers at Ceramic Finishing Company, State College, Pennsylvania, have been trying various surface treatments designed to increase the stress required to cause a surface crack to grow during impact. One approach involves the use of compressive surface stresses, which would tend to cancel stresses occurring during impact or other load. Compressive stresses can be induced by various thermal or chemical means. The bonding of energy absorbing surface layers to the ceramic is another approach being studied.

Composite materials provide an alternative means of altering the properties of ceramics by combining the good properties of the component materials and not the bad. For example, researchers have studied the possibility of dispersing chucks or filaments of silicon carbide as a second phase within silicon nitride in the hopes of combining the toughness of silicon nitride with the superior high temperature creep resistance of silicon carbide.

J. J. Brennan of the United Aircraft Research Laboratories, East Hartford, Connecticut, has been embedding ductile tantalum wires in hot-pressed silicon nitride. At present, silicon nitride made in this way appears to have somewhat lower strength than silicon nitride made without the tantalum wires, and oxidation of the wires can be a problem at high temperatures. However, the resistance to fracture during impact tests is considerably improved, increasing by a factor of 30 in the temperature range from room temperature to 1300°C.

A Silicon Carbide Composite

W. B. Hillig and his co-workers at General Electric have made a silicon carbide composite material. In the GE composite, carbon fibers are shaped appropriately, and the fibers are then infiltrated with molten silicon, which reacts with the carbon, somewhat as in reaction bonded silicon carbide. The result is a composite of silicon carbide fibers in a metallic silicon matrix. This fully dense material can have a range of ductility corresponding to a silicon carbide content of from 20 to 80 percent. The melting point of silicon sets the upper temperature limit for the use of this material.

Silicon carbide and silicon nitride can be prepared by chemical vapor deposition. Unfortunately, because of the difficulties and expense of making large and complex shapes with uniformly good properties, this method has not been widely considered.

R. J. Diefendorf and his associates at Rensselaer Polytechnic Institute have made vapor deposited silicon carbide with about twice the strength of silicon carbide made in other ways. In part, the superior high temperature strength results from the lack of any additives whatsoever, since no densifying step occurs in chemical vapor deposition. Instead a mixture of hydrogen and methyltrichlorosilane (CH_3Cl_3Si) is passed through a furnace where silicon carbide is deposited on the wall of a deposition tube.

When complex shapes are being made, there can be a problem with excess carbon at the grain boundaries. Thus simple shapes in theory are not so difficult to make by chemical vapor deposition, but complex shapes are much harder. Because of this and because of cost considerations, Diefendorf suggests that, if perfected, chemically vapor deposited silicon carbide may be primarily a competitor of hot-pressed or sintered ceramic, but not reaction bonded.

One of the major difficulties in designing with ceramics, in addition to their inherent brittleness, is a statistical nature in their properties which is related to the distribution of imperfections from which cracks leading to fracture can grow. Any given group of ostensibly identical parts may fail at widely differing loads. One concept that has evolved is the strength-probability-time (SPT) diagram. Developed by R. W. Davidge and his associates at the Atomic Energy Research Establishment, Harwell, United Kingdom, the SPT diagram gives the engineer a statistical probability that a part will survive a specified time under a given stress load at a given temperature.

A. G. Evans (now at the Rockwell International Science Center, Thousand Oaks, California) and S. M. Wiederhorn of the National Bureau of Standards, Gaithersburg, Maryland, have taken a different approach by combining fracture measurements interpreted in terms of the slow crack growth model discussed earlier with proof testing in order to calculate minimum failure times for parts that survive the proof test.

The minimum time to fail under a given load can be found from a measured crack velocity and initial crack size. Unfortunately, the cracks are so small that existing nondestructive testing procedures cannot reliably detect them. In a proof test, a load sufficient to cause some samples to fail is applied. The proof stress can be related to the minimum size crack that could result in such a failure and hence to the maximum initial crack size that could be in the remaining samples.

In the article following, the performance of silicon nitride and silicon carbide when used in actual or simulated gas turbine environments is examined.

Making Gas Turbines from Brittle Ceramic Materials

Arthur L. Robinson

Silicon nitride and silicon carbide ceramics used as structural materials could reduce both the energy consumption and pollution emissions of gas turbines. Heat engines made from these ceramics could run at higher temperatures than engines made of even the most exotic high temperature alloys presently available, and fossil fuels could be more efficiently burned than at present. During the last 15 years researchers have learned how to make these ceramics and then have improved them. On the basis of this knowledge, programs are now under way both in the United States and in Europe to demonstrate the use of silicon nitride and silicon carbide in operating gas turbines for highway vehicles, stationary electrical power generators, and remotely piloted aircraft.

In 1971 the Advanced Research Projects Agency (ARPA) began a multimillion dollar program under the direction of Maurice Sinnott (now at the University of Michigan, Ann Arbor) that was designed to leapfrog from the 1100°C maximum operational temperature possible with alloys to about 1370°C, through the use of silicon nitride or silicon carbide ceramics in operating gas turbines. According to Sinnott, at least three factors, in addition to the advancing state of the art, made the silicon-based ceramics look attractive: the possibility of operating at higher temperatures; the ready availability of silicon, carbon, and nitrogen as compared to the need to import elements used in high temperature alloys, such as nickel, cobalt, and chromium; and the prospects for low costs, especially of raw materials.

Ford Motor Company, Dearborn, Michigan, is the prime contractor for the ARPA turbine program, which is somewhat innocuously titled "Brittle Materials Design." Ford has as its goal an automobile-sized 200-horsepower (150-kilowatt) turbine in which all the hot flow path components will be made from ceramics. Hot flow path components include the combustor, nose cone, first and second stage stators and rotors, and regenerator. The demonstration turbine is to operate at temperatures up to 1371°C in the hottest part of the engine over a 200-hour duty cycle, which includes cold starts and rapid shutdowns. The latter two situations are conducive to thermal shock, a condition whereby rapid temperature changes cause ceramics to fracture.

Now in the fourth year of the program with two more years to go, the Ford team headed by A. F. McLean has succeeded in running a ceramic turbine for 100 hours at a maximum temperature of 1050°C. Metal rotors were used in the tests and were responsible for the temperature limitation.

No single ceramic is likely to be best for all the turbine components. Thus, the Ford engineers, while concentrating on silicon nitride, are looking at both reaction bonded and hot-pressed versions (see preceding article on p. 137). The reaction bonded silicon nitride is especially important because of the possibility of fabricating complex shapes at low cost.

Because one cannot simply replace a metal part with the same part made from a ceramic, a major portion of the Ford effort has been devoted to designing the turbine so that the good properties of the silicon nitride will be incorporated and the bad aspects will be avoided. Fabrication methods have also had to be developed. For reaction bonded silicon nitride parts, injection molding (a process common in the plastics industry) and slip casting (a traditional ceramic process) have both been used. Ford has managed to increase the density and hence the strength of parts made by these methods. Before, if the powder shape was too compact, then the nitrogen could not reach and react with all the silicon.

Bonding Rotors a Problem

The major problem has been with the rotors. Because the highest stresses are in the rotor hub, it has been made from hot-pressed material, which is denser and stronger than reaction bonded. The rotor blades, however, have been made from reaction bonded silicon nitride because it has superior creep resistance at high temperatures, and higher temperatures are encountered by the rotor blades than by the rotor hub. Work is under way to solve the problem of achieving a combination of strength, precise alignment, and freedom from defects in the bonding between the hub and the blades.

Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, is a subcontractor to Ford and is charged with developing ceramic nozzle guide vanes (first stage stator) which will withstand 1371°C in a 30-megawatt test gas turbine. The eventual turbine will likely be a hybrid of metal and ceramic parts, with the combustor, first stage stator vanes, and first stage rotor blades being made of ceramics and the remainder from metals, according to R. J. Bratton, manager of the Westinghouse project. A possible application of such a turbine would be in a combined cycle power plant. The gas turbine serves as a first stage power generator whose hot exhaust gases are used to heat steam in the boilers of a second stage steam turbine generator.

A turbine of this size has a stator diameter of about 1.5 meters, as compared with perhaps 15 centimeters in an auto-sized turbine. The large size makes it uneconomical to test very many times, in part because of the high fuel costs. As a result, Westinghouse has placed a great deal of emphasis on theoretical modeling of stresses and heat transfer in the ceramic vanes and less on actual testing.

Both silicon carbide and silicon nitride are being investigated in parallel. The hot-pressed version of each is needed because of stringent materials requirements that cannot be fulfilled by reaction bonded ceramics. There is some evidence to indicate that silicon nitride is superior to silicon carbide for the turbine application, although less engineering data are available on the latter.

In a recent test at 1371°C, dramatic confirmation of the apparently superior toughness under impact of hot-pressed silicon nitride was obtained when an accident caused the temperature to rise to 1600°C and then fall to 315°C within seconds. The metal combustor basket in the test rig had failed and pieces of the basket impacted the silicon nitride and silicon carbide stator vanes being tested. Afterward, it was found that the silicon nitride vanes had survived intact, whereas the silicon carbide vanes (already cracked due to thermal shock) were destroyed.

The ARPA ceramic turbine program has contributed to a revival of interest in ceramics as structural materials. A consortium of (mainly) Department of Defense agencies is now working on turbines for remotely piloted aircraft. A program similar to the ARPA project is under way in Germany. It would thus seem that interest among all parts of the research community is sufficient to make ceramics succeed if it is at all possible.

The author is a member of the staff of *Science* in the Research News section.

Glassy Metals: A Possible New Industrial Material

Arthur L. Robinson

Ever since a primitive blacksmith first discovered that quenching an alloy of iron and carbon with water could greatly increase the strength of the resulting steel, the world of the metallurgist has been heavily weighted toward the proposition that the most useful properties of metallic alloys often result when nonequilibrium structures are obtained. The principal means for obtaining such nonequilibrium structures has been some variation of the quenching process, that is, the cooling of an alloy so rapidly that the equilibrium structure characteristic of the lower temperature does not have time to form and the high-temperature structure is retained.

Now, the fascination of the materials scientist and solid state physicist with amorphous or noncrystalline materials in combination with the older metallurgical idea of quenching is giving rise to a class of solids known as amorphous metallic alloys or glassy metals. There is a growing interest among theoretical and applied researchers alike in the mechanical, magnetic, and electrical properties of these materials.

When a molten metal or metallic alloy is cooled, the solid phase formed is crystalline, with a structure that depends on the particular alloy composition. In contrast, molten glass-forming materials, when cooled, do not assume a crystalline structure, but instead retain a structure somewhat like that of the liquid—an amorphous structure. In each case, the thermodynamically stable or equilibrium structure at room temperature is crystalline. The difference between the two is in the kinetics or rate of formation of the crystalline phase, which is controlled by factors such as the nature of the chemical bonding and the ease with which atoms move relative to each other. Thus, in metals, the kinetics favors rapid formation of a crystalline phase, whereas in normal glasses the rate of formation is so slow that almost any cooling rate is sufficient to result in an amorphous structure. Glassy metals are formed when the molten metal is cooled sufficiently rapidly that crystallization is suppressed.

There are at least four methods of obtaining glassy metals, only one of which involves rapidly cooling, or quenching, a molten liquid, although all in effect quench by suppressing the rate of crystal formation. The other methods are vacuum evaporation, sputtering, and electrodeposition and "electroless" deposition. The first report of an amorphous metal produced by quenching was that by Pol Duwez' group at the California Institute of Technology, Pasadena; they obtained an amorphous alloy consisting of 75 percent gold and 25 percent silicon by propelling small molten globules against a thermally conductive metal substrate at high velocities. Amorphous specimens produced in this way were foils varying from less than 1 to a few micrometers thick. Alloys made by liquid quenching are limited to one of two groups. The first is composed of alloys made from either a transition or a noble metal and a smaller metalloid element, such as alloys of palladium and silicon or iron, phosphorus, and carbon. The second is composed of alloys made from transition metals only (intertransition metal alloys), such as copper-zirconium.

Vacuum evaporation, in which the starting alloy materials are vaporized by heating in some way and then deposited onto a substrate cooled to the temperature of liquid nitrogen (77°K) or below, is a method for producing thin films of amorphous metallic elements, as well as a wider variety of alloys than by liquid quenching. Sputtering, like vacuum evaporation, can be used to make a wide variety of alloy compositions. A target of the desired composition and a substrate are placed in an ionized gas (plasma) maintained by an electric field. The gas ions are accelerated toward and knock atoms from the surface of the target, which are deposited on the substrate to make a thin film with an amorphous structure. Electrodeposition (the familiar nickel-plating process) is used to make alloys of phosphorus and either nickel, iron, cobalt, or palladium.

Most researchers view the amorphous metallic alloys as existing in a thermodynamically metastable phase that can be represented on a modified metallurgical temperature-composition diagram and that is characterized by a well-defined glass transition. The glass transition is in some respects analogous to the phase transition between the liquid and the crystalline solid. In practice, the glass transition is usually observed by measuring the heat capacity as a function of increasing temperature. Near the glass transition, the heat capacity rises rapidly, and it is this rise that is used to mark the temperature of the glass transition. Such measurements were first made in gold-silicon alloys by H. S. Chen (now at Bell Telephone Laboratories, Murray Hill, New Jersey) and David Turnbull of Harvard University, Cambridge, Massachusetts.

The structure of amorphous alloys is thought to be similar to that of liquid metals. One of the first attempts to model the structure of a liquid was that by the late J. D. Bernal of the University of London, who packed hard ball bearings into a rubber vessel in such a way as to obtain the maximum possible density. The resulting dense random-packed (DRP) structure has been the basis for most current attempts to model the structure of amorphous metals.

Calculations of interatomic spacings and the density of the alloy based on Bernal-type models have usually agreed well with the experimentally determined values from measurements on alloys consisting of a noble metal or a transition metal with a metalloid, according to G. S. Cargill III, of Yale University, New Haven, Connecticut, although small discrepancies remain. One difference between real alloys and hard spheres is that the components of an alloy have different sizes, so that models based on two sphere sizes might be more appropriate for a binary alloy. D. E. Polk, now at Allied Chemical Corporation, Morristown, New Jersey, suggested that the smaller metalloid atoms might fit into holes or interstices in the DRP structure of the larger metal atoms. An approximation of a two-sphere DRP model can be constructed with the use of the local atomic configurations of the one-sphere DRP structure by extending them to two sizes of spheres. Cargill now thinks that calculations based on this approximate model indicate much better agreement with experiment than older models. A complete two-sphere structure has yet to be built and analyzed, however.

The main competitor to the DRP model of an amorphous metal is the microcrystallite model, in which the solid is envisaged as being composed of very small crystalline volumes (with dimensions as small as 10 to 30 angstroms) separated by highly disordered regions—that is, a structure like that of a normal metal, but with a nearly vanishingly small grain size. For the most part, investigators of the properties of amorphous metals have decided in favor of the DRP-like amorphous structure, re-

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serving the microcrystallite model for those alloys not cooled sufficiently rapidly to completely suppress crystallization.

Most recently, for example, P. Chaudhari, at IBM's Thomas J. Watson Research Center, Yorktown Heights, New York, has found that the results of x-ray and electron diffraction measurements and of high-resolution transmission electron microscopy on both amorphous semiconductors and metals were consistent only with amorphous random-packed structures. John Vander Sande and Nicholas Grant, at the Massachusetts Institute of Technology, Cambridge, have also used a high-resolution electron microscopy technique, in which the presence of crystal lattice planes could be seen in crystallites as small as 25 Å across, but they observed no lattice planes in amorphous copper-zirconium alloys. Finally, Stewart Solin of the University of Chicago, Chicago, Illinois, on the basis of Raman scattering measurements on microcrystallite and amorphous forms of silicon, diamond, and graphite, found that amorphous semiconductors are not microcrystalline, and by inference, neither are amorphous metals.

A primary reason for the considerable interest in the structure of glassy metals is the wide range of new phenomena that these materials exhibit. For example, one of the most promising properties of amorphous metals is their high strength. Most recently, the Allied Chemical Corporation has announced the development of a new group of glassy metals with high strength and ductility, which can be manufactured inexpensively, in technologically useful quantities and at high rates. The combination of high strength and ductility is extremely desirable. In usual crystalline materials, in contrast, one finds an inverse relation between the two properties—a high strength goes with a low ductility and vice versa. According to Carl Cline at Allied, one can foresee applications involving high-strength wires and ribbons in a variety of areas, although the relatively low temperature at which many amorphous metals crystallize when they are heated may impose some limitations. The ability to overcome what has long been a problem in the area of amorphous metallic alloys, the production of specimens in sizes and shapes suitable for use in practical applications, combined with the relative inexpensiveness of the materials used in Allied's alloys indicates that amorphous materials have entered the stage of being commercially exploitable.

Amorphous metals often exhibit strengths near the theoretical limit of crystals of the same material and are many times stronger than most crystalline materials. Polk and C. A. Pampillo at Allied Chemical Corporation, for example, reported nickel-iron and iron amorphous alloys with fracture strengths (applied stress before the alloys fractured) of the order of 375×10^3 and 350×10^3 pounds per square inch, respectively. Although these alloys are among those developed by Allied specifically for their high strengths, two of the most commonly studied amorphous metal alloys (because they are so easily formed compared to other alloys), palladium-silicon and nickel-phosphorus, have tensile strengths of 200×10^3 and 125×10^3 pounds per square inch, respectively, indicating the pervasiveness of the high-strength characteristic throughout the range of amorphous metallic alloys.

Fig. 1. Scanning electron micrograph of the fracture surface of a glassy metallic alloy deformed by torsion inside the microscope. [H. J. Leamy, Bell Telephone Laboratories]

Harry Leamy and his co-workers at the Bell Telephone Laboratories have studied the deformation and fracture of glassy metals. Leamy reported that, in tensile tests of amorphous palladium-silicon, approximately 10 to 40 percent shear deformation occurred, mainly on a single plane oriented at about 45 degrees to the tensile axis. The sample then fractured by decohesion along the same plane. In scanning electron microscope examinations of the morphology of the fractured surface, two regions were observed: a relatively featureless area corresponding to the region where plastic shear has occurred, and an area characterized by, in Leamy's words, "a river pattern of local necking protrusions" (Fig. 1) where the rupture occurred. This morphology is quite different from that occurring in crystalline metals, and one explanation is that, in localized high-stress regions, the amorphous metal is heated to a temperature above that of the glass transition and becomes much less viscous, enabling local plastic flow to occur and subsequently complete failure.

Similar studies of fracture in copper-zirconium alloys by R. Ray and B. C. Giessen at Northeastern University, Boston, Massachusetts, resulted in the observation of morphologies nearly identical to those in palladium-silicon. Thus, the same fracture mechanism may be common to all amorphous metals.

The large, localized shear deformation in palladium-silicon suggests the existence of dislocations, the line defect whose motion through crystalline materials is responsible for their relatively low strengths. Many scientists, including J. J. Gilman of Allied Chemical Corporation, believe that dislocation motion is a deformation mode in amorphous materials, and that the high strength of amorphous materials is due to the higher resistance to dislocation motion associated with the disordered structure of amorphous metals. J. C. M. Li of the University of Rochester, Rochester, New York, using a dislocation model for disordered materials, calculated that dislocation motion as a deformation mode required about half the stress that a uniform deformation would require and that this stress was close to experimentally observed shear stresses. He also noted that the definition of a dislocation as the boundary between deformed and undeformed (or more accurately between slipped and unslipped) regions in a metal is sufficiently general to apply to any kind of structure in which localized deformation could occur and is not restricted to crystals.

On the other side of the argument, Grant at MIT pointed out that he has never observed any plastic elongation in any of his copper-zirconium alloys and suggested that observation of such plastic deformation and of dislocation produced slip lines might be taken as evidence of microcrystallites rather than a random amorphous structure.

Not only are the mechanical properties of amorphous metals being extensively studied, but the magnetic properties of amorphous metals are attractive because of possible practical applications as well as for understanding the theory of disordered materials. The first prediction of ferromagnetism in disordered materials is widely attributed to A. I. Gubanov of the U.S.S.R. He showed that quantum mechanical exchange interactions between nearest magnetic neighbors in disordered structures could result in ferromagnetism. Shortly afterward, experimental confirmation of this prediction was made by several investigators in a variety of amorphous alloys.

Amorphous Bubbles

The magnetic alloys of the most current interest are those usable in magnetic bubble domain devices. Previously, bubble domain materials have been crystalline

thin films that have their magnetization oriented preferentially either up or down, perpendicularly to the plane of the film. They can be used as memory and storage devices in computers by controlling the generation and motion of "bubbles" – circular regions whose magnetization is oriented oppositely to that of the rest of the film.

This year, Chaudhari and his coworkers at IBM's Thomas J. Watson Research Center announced the production, by sputtering, of amorphous antiferromagnetic gadolinium-cobalt and gadolinium-iron alloys that also exhibited the required perpendicular orientation of the magnetization. Chaudhari thinks that sputtered atoms arriving at the substrate surface move to certain energetically favorable sites and in this way build up a preferred orientation that otherwise would not be expected for the isotropic DRP structure.

Bubble domain devices also make use of another magnetic property that is characteristic of amorphous magnets – the magnetic softness – so that amorphous materials are both easily magnetized and demagnetized with only a low applied field, a necessity for rapid writing and erasing of bits of information in a computer memory or storage device. Chaudhari further noted that the wide range of compositions obtainable in amorphous alloys produced by sputtering provides a degree of tunability of the properties of the alloy. For example, most amorphous magnets have a lower Curie temperature than the corresponding crystalline alloy of the same composition. Recently, however, workers at IBM have produced a gadolinium-cobalt alloy with a higher Curie temperature by adjusting the alloy composition.

Efforts are being made to obtain a basic understanding of the nature of magnetism in amorphous materials. Mössbauer effect measurements provide a means of studying the local environment of atoms in both magnetic and nonmagnetic amorphous alloys and were first used by C. C. Tsuei and co-workers in the amorphous alloys group at Caltech (Tsuei is now working at IBM) to study magnetic iron-phosphorus-carbon alloys. According to Giessen at Northeastern University, who has reported Mössbauer studies with the iron-57 isotope in copper-zirconium alloys, the multiplicity of different local anisotropic environments tends to smear out the details of the Mössbauer spectra and thus far has prevented the elucidation of the details of the local structure. Magnetization and electrical resistivity as a function of temperature and neutron scattering are among other techniques used to unravel the magnetic structure of amorphous alloys.

Amorphous metallic alloys have other properties that may find practical application in specialized situations. As just one example, workers at both Bell Telephone Laboratories and Allied Chemical Corporation are interested in the ultrasonic attenuation properties of palladium-silicon alloys. It is believed that the low attenuation of the amplitude of acoustic waves in passing through these alloys may find application in a number of acoustic devices, such as delay lines in microwave signal processing circuits.

The field of amorphous metallic alloys has now entered the stage where an acceleration of scientific interest in the properties of disordered solids combined with the possibility of imminent commercial exploitation has conferred an aura of respectability to what was once a "far out" laboratory curiosity. While it seems clear that the level of interest in the scientific community will remain high for some time to come, it remains to be seen to what extent practical applications will follow.

New Materials: A Growing List of Nonmetallic Metals

William D. Metz

Two years ago, scientists working in materials research were extremely excited by the announcement that a certain organic salt – which contains no metallic elements – showed signs of superconductivity. The conductivity of this particular salt, called TTF-TCNQ, increased as it was cooled below room temperature, until a very high value was reached at 58°K. A superconducting material at that temperature would have far outclassed the best of the "high temperature" superconducting metals which becomes lossless at 23°K.

The promise of superconductivity for TTF-TCNQ was never realized, but the material nevertheless enticed many researchers to study nonmetallic metals. The conduction properties of organic crystals were largely unknown at the time, and the novel behavior of TTF-TCNQ, plus the possibility of synthesizing many related salts by the techniques of organic chemistry, were more than enough to stimulate further research. That research has borne fruit, as there are now nearly a dozen similar materials known. Besides being unusual for the fact that they are conducting at all, these materials behave like one-dimensional metals in that they conduct strongly in one direction but not in others. Lastly, the possibility of superconductivity has not proved irrelevant. One material, a polymer of sulfur and nitrogen, does undergo a transition into a superconducting state – albeit at 0.3°K.

Although the organic salts and the sulfur-nitrogen polymer are not perfectly analogous, they nevertheless have many similarities. The polymer is a long chain of alternating atoms of sulfur and nitrogen, in which the predominant direction for conduction is up and down the chain. The individual polymer chains can bond together loosely to form a crystal. Covalent bonds connect the atoms in each polymer, and weaker bonds align the polymers with each other in such a fashion that sulfur and nitrogen atoms alternate in an orderly crystal structure.

Family of TCNQ Salts

The organic salts are composed of the elements nitrogen, hydrogen, carbon, and sulfur or one of its possible replacements from the same column of the periodic table. The organic salts are not, strictly speaking, polymers, but they also tend to conduct in a single direction, which is along a backbone formed by stacks of repeated units in the crystal structure. Most organic crystals studied so far have been salts of TCNQ (tetracyanoquinodimethane) in which the positive ion was TTF (tetrathiofulvalene) or a variation of it. Both these molecular forms are planar so

The author is a member of the staff of *Science* in the Research News section. This article is reprinted with minor author corrections.

that they can be easily stacked, and the structure of the TTF-TCNQ crystal is generally thought to consist of parallel columns of separately stacked TTF and TCNQ molecules.

Because of the long repeated structures of the polymer of sulfur and nitrogen, $(SN)_x$, and the TCNQ salts, they are highly anisotropic. Both classes of materials have ratios of 100:1 or more for measured conductivity parallel to the structural axis versus conductivity perpendicular to it. This property suggests a number of possible industrial applications, particularly as a polarizer that could be used in integrated optical communications circuitry. The superconductivity discovered in $(SN)_x$ is of course at too low a temperature to conceivably be useful, since even liquid helium refrigerators do not routinely cool materials to 0.3°K.

The present burst of activity in the study of exotic, quasi-one-dimensional metals began in 1973. In April of that year, Alan J. Heeger, Anthony F. Garito, and associates at the University of Pennsylvania, Philadelphia, announced that three of seventy crystals of TTF-TCNQ that they had tested showed superconducting fluctuations at 58°K [*Science* **180**, 1041 (1973)]. Superconducting fluctuations occur when small regions in a crystal are fluctuating between the superconducting state and the normally conducting one. Many materials show superconducting fluctuations, then go on to become completely superconducting at still lower temperatures. However, TTF-TCNQ changes into an insulator at temperatures below 58°K. The very high conductivity peaks that were interpreted as the evidence for superconducting fluctuations were not confirmed by other researchers. Many solid-state scientists think the original high conductivity peaks were an artifact of the particular experimental method used. Nevertheless, the hints of extraordinary properties were sufficiently strong that at least six laboratories in the United States began to devote considerable effort to the study of TTF-TCNQ and related compounds.

At least eight TCNQ salts have now been synthesized with donor molecules similar to TTF, which has two coupled five-member rings, each containing a pair of sulfur atoms. Many of the variations have been synthesized by Dwaine Cowan, Aaron Bloch, Ted Poehler, and associates at Johns Hopkins University, Baltimore, Maryland, where research on organic conductors started at least 4 years ago. Extensive research on materials of the TTF-TCNQ type has also been done at the International Business Machines (IBM) laboratories in Yorktown Heights, New York, where Bruce Scott and his co-workers synthesized the first selenium analog of the TTF molecule.

The more highly conducting organic crystals are those in which the donor and acceptor molecules form separate conducting stacks. These are technically semimetals, since the conduction band energies for the two stacks are only weakly overlapping. In the semimetal category, the more conducting crystals are thought to be those with small and easily polarizable donor molecules. In addition, both donor and acceptor molecules should be symmetric, according to Aaron Bloch, so as not to become structurally disordered at low temperatures and thus undergo a transition to become an insulator. Most of the TCNQ salts undergo a metal-insulator transition (Peierls transition) at temperatures in the range 40° to 80°K.

Very recently, the researchers at Johns Hopkins have found a new organic charge transfer salt which has the highest room-temperature conductivity of any known organic substance. Perhaps more importantly, the new salt, HMTSF-TCNQ, is the first organic conductor based on the TTF-TCNQ prototype that does not undergo a metal-insulator transition. Work by the Johns Hopkins group has shown that HMTSF-TCNQ behaves electrically as a metal in the temperature range from 300° to 1.1°K, and they, in cooperation with R. L. Greene of the IBM laboratories in San Jose, California, and his co-workers at Stanford University, have extended the result down to 0.008°K. The new donor molecule, HMTSF (hexamethylenetetraselenafulvalenium), represents a considerable success because the insulator state has been suppressed. However, HMTSF-TCNQ does not appear to become superconducting, according to Greene and his co-workers, even at very low temperatures.

Even though the flexibility of organic chemistry offers the hope of fine control over conduction properties in a way that is not possible with elemental metals, the logical progressions for synthesizing new materials have not proved simple in practice. One reason is that HMTSF is considerably more difficult to synthesize than TTF because less is known about the preparative chemistry of selenium than sulfur, and because selenium is very toxic. Tellurium substitutions might yield even better conduction properties than selenium substitution, but work with tellurium is "really grim," according to the Johns Hopkins researchers.

Unlike the TCNQ salts, which were first synthesized by Du Pont researchers in the 1960's, $(SN)_x$ had been known for more than 50 years. In 1910, Frank Playfair Burt, then at the University College, London, reported that "a new sulphide" of nitrogen which he identified as $(SN)_x$ afforded "an interesting example of inorganic polymerism." However, the conducting properties of $(SN)_x$ were not investigated until 1962 when Mortimer Labes at Temple University in Philadelphia measured the d-c conductivity of fibrous crystals of the polymer. When Labes reported this work at the 1974 Lake Arrowhead Symposium on Conducting Organic and Transition Metal Salts, where most of the researchers studying TTF-TCNQ heard it, the two research efforts merged.

First Superconducting Polymer

What Labes found was that $(SN)_x$ remained conducting from room temperatures down to 4.2°K, without undergoing a Peierls transition. Within a short time, researchers at IBM, San Jose, had prepared their own crystals of $(SN)_x$ and made low-temperature (10° to 1.5°K) specific heat measurements that indicated the polymer would remain metallic at even lower temperatures. Shortly afterward, Greene, and Bryan Street, along with Laurance Suter of Stanford University, Palo Alto, California, established that the transition to the superconducting state occurred between 0.25° and 0.28°K for three different crystal samples. The discovery was the first time superconductivity had been found in a polymer.

The discovery was perhaps less shocking to those who had seen $(SN)_x$ crystals, which are shiny, with a bronze metallic luster, and are almost as conducting as mercury.

The new superconductor grows as a bundle of crystal fibers. To grow the fibrous crystals is a fairly tricky process that starts with the vacuum sublimitation of S_4N_4. According to the University of Pennsylvania group, the material is deposited as a dimer, S_2N_2, which is in crystalline form. The S_2N_2 structure is a square planar ring. Over the course of many hours at room temperature polymerization takes place, as one bond on the square ring breaks and attaches to an adjoining S_2N_2 molecule. The result is a long chain of repeated SN monomers.

Considerable variation is found in the properties of different samples of $(SN)_x$. The bulk crystal separates into many fibers because of large-scale defects in the crystal structure, but, according to Ray Baughman at the Allied Chemicals laboratories in Morristown, New Jersey, the process of solid-phase polymerization also introduces many molecular-scale defects. According to Baughman, the spatial symmetries of the S_2N_2 and $(SN)_x$ crystals are similar,

but the unique axis of the polymer does not correspond to the unique axis of the dimer. Therefore, a flipping of the axis must occur during polymerization. There are two ways in which the final crystal can be formed, and this bifurcation introduces a randomness to the reaction that results in many chains that are not in their natural positions in the crystal lattice. According to Baughman and co-workers at Allied Chemicals and University of Pennsylvania, in the final state as many as 27 percent of the chains are in disordered positions.

The amount of molecular-scale crystal disorder is an important variable that may conceal the intrinsic conducting and superconducting properties of $(SN)_x$. The crystal defects along the axis of the fibers add to the electrical resistance of a sample of $(SN)_x$, and the defects also give rise to residual resistance that is present in some samples even after the crystal has clearly made a transition to a superconducting state.

From both electron diffraction studies and x-ray diffraction studies, models of the crystal structure of $(SN)_x$ have been proposed, first by M. Boudeulle at the Claude Bernard University in Lyon, France, and more recently by the University of Pennsylvania group. The two structures are very similar. The polymer is almost planar but not at all straight, as the atoms in the ring structure of S_2N_2 do not move very far during polymerization.

Using either crystal structure, the conduction band energies of $(SN)_x$ can be calculated, with the general result that $(SN)_x$ has a conduction band that is about 1 electron volt wide and has the properties of a semimetal with pockets of electrons and holes. From consideration of the crystal structure, it is not yet clear whether $(SN)_x$ is one-dimensional or not. There are weak interchain bonds that may contribute to electrical communication between polymer chains.

Dispute over Dimensionality

From consideration of the conducting properties, it is clear that $(SN)_x$ cannot be perfectly one-dimensional, or it would not become superconducting at all. Fluctuations occur randomly throughout any material that is approaching a superconducting transition, and "normal" regions are only locked into the superconducting state by the influence of neighboring regions. But in a one-dimensional chain, one "normal" link stops such communication completely, and there would be no way for the number of normal regions to steadily decrease. Calculations of the band structure by several research groups tend to support a two- or three-dimensional system. Optical measurements including reflectivity and plasma studies by the University of Pennsylvania group and others also indicate an anisotropy characteristic of three-dimensional systems; researchers at Temple and Brown universities, however, report evidence of a one-dimensional system.

Where the debate over the dimensionality of $(SN)_x$ will lead is uncertain. A number of researchers had suggested that $(SN)_x$ offered the first opportunity to test theories of superconductivity in a one-dimensional system. It is generally expected that $(SN)_x$ will obey the conventional Bardeen-Cooper-Schrieffer theory of superconductivity that has been so successfully used to explain metals; other superconducting theories might also be tested.

Although most tests of $(SN)_x$ have been carried out on bulk crystals, usually a few millimeters long and fractions of a millimeter wide or high, the growth of thin films of the polymer has also been reported. At the University of Pennsylvania, Heeger, Alan MacDiarmid, and Garito have prepared the first fully oriented crystal films. The films were produced by epitaxial growth on various materials including Mylar, Teflon, and polyethylene, and are reported to be analytically pure and free of trace S_2N_2 contaminants. Epitaxial growth is a form of crystal deposition in which the structures of the substrate and the growing crystal are sufficiently similar that one can be used to form a pattern for the other.

Electronic and Optical Applications

The thin films of $(SN)_x$ could be particularly useful as polarizers, because light rays polarized parallel to the conducting axis of the film (which is the same as the fiber axis) are reflected more strongly than rays polarized perpendicular to the axis. Since the usefulness of $(SN)_x$ as a polarizer is derived from the anisotropic conduction properties of the material rather than from its superconducting properties, the salts based on TTF-TCNQ might also have optical applications.

Industrial support for research on exotic one-dimensional conductors has followed a pattern in the last few years that also suggests that optical properties may be the most useful aspects at present. Four years ago Monsanto researchers began studying TTF-TCNQ because of its high thermoelectric power capability. Most of the organic conductors produce electrical power when heated, and this property can be used for refrigerators and small power sources. (Propane-fired lead telluride units have been marketed for use in place of batteries.)

Monsanto was reassessing its research in 1973 when the superconducting fluctuations of TTF-TCNQ were announced and decided to continue. But it has now stopped all research on the exotic one-dimensional conductors. Monsanto researchers concluded that the most likely applications were in electronics or optics, which are not fields where Monsanto has had a traditional interest. Du Pont also showed some interest and then dropped the subject.

The interest in basic research on these materials remains quite strong, however. Most laboratories have emphasized research on $(SN)_x$ over TCNQ salts during the last 6 months, but there is evidence now that they are returning to a program that balances research on organic and inorganic conductors more evenly. At the Bell Laboratories in Morristown, New Jersey, Fred Wudl is experimenting with different acceptor molecules, to possibly replace TCNQ. Others are trying to think of ways to synthesize structures similar to $(SN)_x$, such as the replacement of sulfur with selenium in that molecule. Still others talk of the possibility of synthesizing organic conducting polymers.

Behind it all may be the hope of unusual superconductivity, but there is no doubt that this class of compounds has many novel properties that are worthy of further study.

Materials for Advanced Energy Technologies

Richard S. Claassen

Materials and energy are inextricably linked. Industrial materials cannot be produced without energy, nor can energy be produced without specialized materials. For example, the recovery and processing of industrial materials required about 16 percent of the total U.S. energy consumption in 1974. The interdependence of the two has been increasing and will continue to increase with time as the more easily won raw materials are exhausted and as the energy conversion and utilization schemes become more sophisticated. Although research and development on ways to recover and process materials with less energy is a challenging opportunity for the materials community (*1*), I will focus on the materials technology that will be required in major developing systems for extracting, converting, distributing, and using energy.

Figure 1 is a schematic representation of the energy sources; methods of processing, conversion, transmission, and storage; and forms of fuel energy that may exist in the near term (about 1990). The boxes with hatching indicate the elements which I believe require significantly improved materials technology if meaningful contributions are to be made to the national energy balance. At a later time breeder reactors may be added as converters of uranium, and eventually some form of pure fusion may provide an entirely new source of energy. The successful development of these new nuclear energy technologies will be heavily dependent on achieving substantial improvements in the performance of materials.

The fact that most fuel sources must be processed in some way or converted to another form before they are suitable for consumption is emphasized in Fig. 1. With the exception of solar heating, all systems being considered in this country for replacement of petroleum and natural gas depend on processing and conversion; that is why materials will dominate the resolution of our energy problem. Diminishing supply of low-cost and easily obtained fuels, increased environmental protection measures, and fuel conservation through increased efficiency are all factors which combine to place higher performance demands on every part of the energy supply system. Development of higher-temperature or longer-wearing materials, for example, can yield improvements for every step in Fig. 1. For some elements in the newly evolving program, indicated by hatching in Fig. 1, a significant materials development or improvement is essential to economic operation or even technical feasibility. I will emphasize those elements after some observations on availability of materials.

Supply of materials. Since the shortfall of domestic petroleum supplies was dramatized by the Arab boycott, it has been natural to ask whether there will also be shortages of the materials required to implement our new energy programs. I believe the answer is "No," but it is easy to point out a number of examples where careful attention and action are required (*2*).

1) High chrome alloys are needed for virtually every energy use—from oil refinery pipes to cryogenic structures in the magnets used in magnetic confinement fusion reactors. For chromium we are completely dependent on foreign sources of unknown future political stability.

2) Gallium arsenide cells are attractive for solar photovoltaic use, but a simple computation indicates that for even 8×10^6 watts, 10 percent of the estimated electric generation capacity in 1990, 10^3 tons (metric) of gallium would be required compared to an estimated world resource of 1.1×10^3 tons (*3*).

3) Through catalytic oxidation, fuel cells provide direct conversion of hydrogen-rich fuels to electricity. They offer unique advantages for some applications. The most successful fuel cells, however, require an investment of 20 grams of platinum catalyst per kilowatt, and about one-fifth of that is consumed per year. Use of fuel cells to produce 10 percent of the nation's estimated electrical energy in 1990 would consume about 32 million grams per year, compared with the total world production of about 50 million to 70 million grams per year.

Problems like these, however, can be avoided by adequate forethought. Since the energy program, for example, requires only a few percent of this country's consumption of chromium, the heavy cosmetic use of chromium could presumably be diverted, if necessary. To satisfy needs for corrosion-resistant materials, alloys in which aluminum is used instead of chromium to form passive film could be further developed. Solar cells designed for large applications will be based on more abundant materials such as silicon or copper and sulfur. To avoid the platinum supply problem in fuel cells, molten carbonate cells are under development in which nickel-base electrodes perform the catalysis.

Although the materials supply problem in our energy program can be contained by early system studies and careful design, full development of suitable materials obviously takes many years. Careful thought must be given now to future requirements.

Bulk resource materials may be available in adequate supply to support the energy program, but there may still be shortages of special end products. Steel pipe for oil wells is in short supply. Thick steel plates of large dimensions are needed for steam pressure vessels and for coal gasification reactors at a rate twice that of the projected supply (*2*). The near-term energy program will create a heavy demand for large forgings for turbines, generators, and pressure vessels, probably beyond the present capacity of the industry. Coal cars, draglines, and mine trucks are items with long lead times for delivery. Considerably improved definition and forecast of the needs of particular types and forms of materials for the energy program will be required to enable industrial suppliers to expand capacity sufficiently to support the energy program.

In discussing the sequence of materials developments that will be required for new energy technologies, it is convenient to identify three time periods—the near term, midterm, and long term. I use these categories in the sense that some significant contribution could be made to the nation's energy flow during each period. Implied, in turn, is completion of development and design, followed by considerable investment in construction. Advocates of a particular energy scheme may quarrel with my assignments, but any general understanding

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of the materials-energy problem requires a realization that most new technologies will take considerable time to make a significant impact. On the other hand, the investment in specialized materials development must be made in the next few years or the new materials will not be available when needed.

Near Term—Now to 1990

Coal must relieve the pressure on petroleum and natural gas supplies for the near term. By refining it or by adequate stack scrubbing, we can burn more coal. To directly offset petroleum consumption, coal must be processed to achieve two major objectives: (i) the reduction of sulfur and other undesirable pollutants, and (ii) conversion to a liquid or gaseous form. Many schemes and processes to achieve these objectives are under development (*4*). At the simplest conceptual level, it is just a matter of adding hydrogen in the proportion necessary for the end product desired. Figure 2 illustrates the ratio of hydrogen to carbon in various fuels. Fortunately, the process of adding hydrogen can be designed to remove most of the sulfur, since hydrogen sulfide is more thermodynamically stable than the organically bound sulfur or iron disulfide in coal.

Present commercial schemes for producing hydrogen gas use petroleum derivatives as feed materials, but in the future it will be necessary to recover hydrogen from water by using the combustion of carbon as the energy source. The reaction of separating water into O_2 and H_2 is energetically expensive, requiring 57 kilocalories per mole (0.24 megajoule per mole), although a high fraction of this energy will be recovered later from the hydrocarbon fuel.

Coal liquefaction. The coal conversion most appealing for the near future is therefore the one that adds the least hydrogen—liquefaction; that is, coal is sufficiently hydrodesulfurized to produce a material that can be pumped through pipelines and fired in large boilers to produce electricity or process heat. In 1974, the United States consumed 3.4 quads (*5*) of natural gas and 3.3 quads of oil in electric generating plants (*6*). Suitably liquefied and purified coal, 3.1×10^9 tons per year, could be substituted for these precious fuel forms.

The several coal liquefaction processes under active development transport mixtures of coal and liquid or gas at high temperatures (700° to 730°K or 800° to 850°F) and pressures of several thousand pounds per square inch (psi) gauge. The combination of sulfur and particulate matter makes these streams extremely destructive to the piping, valves, and containers, especially when the flow changes direction. The most frequently used erosion-resistant engineering materials (Stellite and cobalt-bonded tungsten carbide) are subject to some corrosion in sulfidation environments, so new materials of longer life are needed.

It may be necessary to exploit surface protective techniques such as reactive vapor deposition of refractory carbides and nitrides, or fused salt electroplating of refractory alloys. Control of the microstructure and internal stress of protective coatings may be the key to eventual success.

Coal gasification. Coal gasification methods are categorized in three principal groups according to energy content in the product: (i) low Btu (obtained by reacting air and steam with coal), intended principally for on-site generation of electricity; (ii) medium Btu (obtained by reacting oxygen and steam with coal), intended primarily as feedstock for production of methanol; and (iii) high Btu (methane), intended for direct replacement of natural gas in existing distribution systems. The many technical approaches within the categories share a number of serious materials problems. Those for the high-Btu process are most serious, yet representative (*7*).

The Lurgi process, developed decades ago in Germany, has been successfully operated for years to produce low- and medium-Btu gas. This process is limited technically because it can use only certain types of coal feed and economically because it is not readily scaled to large size. The newer processes for coal gasification use more universal schemes for introducing coal and promise lowered cost through larger size and higher pressure of operation. High-pressure reaction gives greater throughput and shifts the chemical equilibrium $2H_2 + 2CO \rightleftharpoons CH_4 + CO_2$ toward methane, so that less hydrogen must be added in the final methanation step. But it is this combination of high pressure and large volume that leads directly to the first major materials problem.

The heart of a coal gasification plant is the reactor vessel, wherein the coal is reacted with oxygen and steam to produce a gaseous mixture of methane, carbon mon-

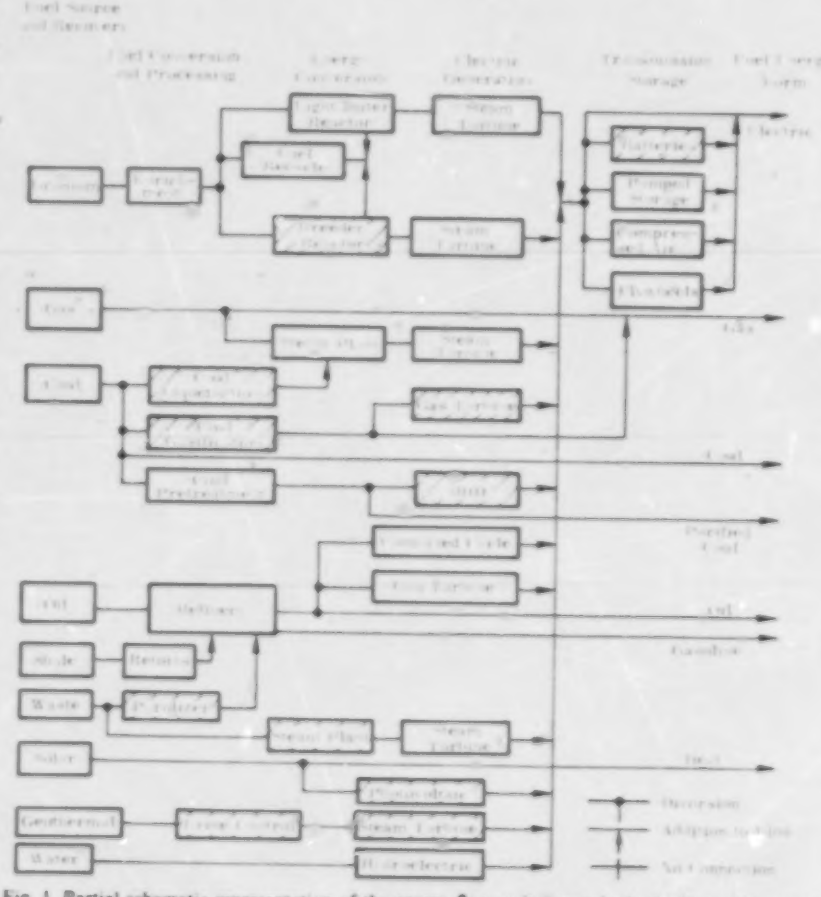

Fig. 1. Partial schematic representation of the energy flow as it may exist in the United States in 1990 when the first four fuel sources will probably still contribute more than 95 percent of the total. Note that the energy sources under development for the future depend on processing or conversion. Boxes with hatching show steps for which new materials are essential.

oxide, and hydrogen along with carbon dioxide, water, hydrogen sulfide, and other impurities. To maximize the methane content, the pressure may be 2000 psi and the temperature between 1150° and 1250°K (1600° and 1800°F) for high reaction rates. These temperatures are well above the working strength of steel—about 730°K (850°F)—so a thick ceramic liner like high-density alumina must be provided to insulate the steel surface. The vessel will be subjected over long periods to extremely aggressive environments, and the problem will be aggravated by the thermal stresses accompanying any necessary shutdowns of the reactor. The normal method for increasing the resistance of ceramic material to chemical and mechanical degradation—increasing the density—decreases the desired insulating property. A material satisfying both conflicting requirements must be developed and evaluated in the actual environment of the reactor.

The reactor vessel may reach 7.6 m in diameter and 76 m in height (25 by 250 feet), weighing as much as 1500 tons in the largest of these units (7). Even the "small" vessels in the high-pressure, high-temperature plants under consideration may be larger than the pressure vessels in a typical nuclear power plant. The high-strength steel exposed to 700° to 730°K (800° to 850°F) will be subjected to a high-pressure hydrogen environment for many years of operation. Should the reactor suddenly be shut down for some operational emergency, the temperature of the steel will drop rapidly, trapping the hydrogen at pressures far above its equilibrium value. Microcracks and voids may be introduced as the steel is again heated to operating temperature, providing potential nuclei for subsequent cracks or fractures. These phenomena must be much better understood so that any necessary modifications to steel alloys can be made before large reactor vessels are built.

The mood of the country is such that major engineering failures will no longer be tolerated. Since a reactor vessel may cost as much as a half-billion dollars, financial arguments also preclude the loss of a reactor through destructive failure. The need to virtually guarantee no failure during the operating lifetime puts great pressure on the design, evaluation, and testing of such reactors, including all aspects of the materials. The problem is challenging indeed, because the operating conditions threaten to be more severe than any experienced to date, yet at the same time the reactors are so big as to require field assembly. We have no procedures for automated welding of such large-volume vessels in the field and no proved techniques for nondestructive field testing of large-volume vessels with walls 30 cm (1 foot) thick. The difficulties we have experienced with the high-pressure tubing of the steam portion of pressurized water reactors should alert us to the magnitude of effort that will be required to satisfactorily develop large reactor vessels. A promising material for the pressure vessel is 2¼ percent chromium 1 percent molybdenum steel.

The second major materials problem in coal gasification is the erosion-corrosion of components that must contain or control moving fluids containing particulates. This problem is similar to that in coal liquefaction, but is possibly worse in gasification because of the higher temperatures and higher stream velocities involved. Because we have little experience in this area, considerable knowledge must be gained before we can understand the processes. New specifications must be developed and more definitive test and evaluation techniques proved before we can design adequate materials for long life and high reliability.

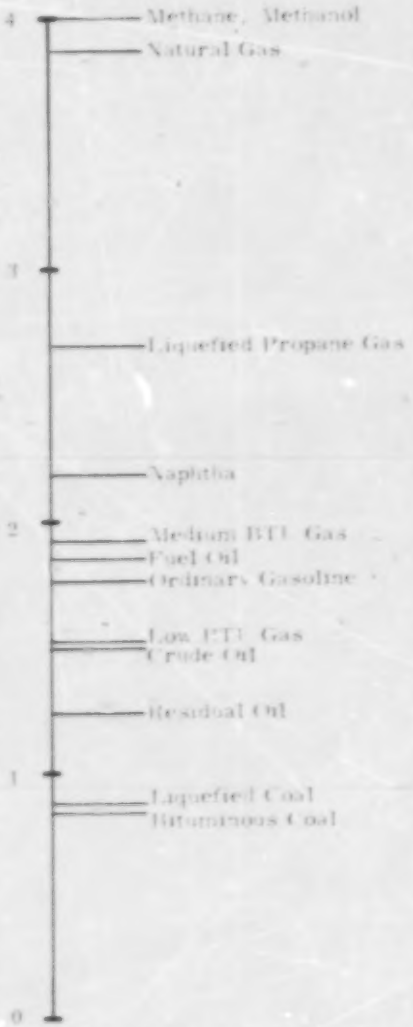

Fig. 2. Atomic hydrogen/carbon ratios for various fuels. Additional hydrogen, amounting to about 0.35 unit on this scale, is required for coal liquefaction. Most of it combines with sulfur and oxides in the coal to create hydrogen sulfide and water.

So little is known about the response of materials under these conditions that there is no obvious candidate. High-temperature alloys of chromium, iron, and nickel selected for resistance to scaling, sulfidation, and phase changes must be evaluated. Coating with refractory materials like alumina or zirconia may be required to protect the alloys from erosion.

Water-moderated reactors. An enormous amount of effort has been spent on materials for nuclear reactors: understanding radiation effects, evaluating materials in test reactors, and the like. The materials that form the neutronic system have performed satisfactorily; however, difficulties in the secondary steam system have led to excessive downtime. Stress corrosion has caused leakage in the tubes, particularly at positions where local geometry causes stagnation. One manufacturer has shown that this problem can be greatly reduced by controlling the alkalinity of the water to a narrow range by buffering with a mixture of disodium hydrogen phosphate and trisodium phosphate. Materials with greater resistance to stress corrosion should, nevertheless, be developed as one step toward demonstrating more reliable performance of power reactors.

Municipal waste. The energy content of recoverable organic waste produced in this country is now greater than 2 quads per year and is increasing in proportion to the population. Most of the recoverable energy is contained in municipal waste, which is a mixture of metals, glass, dirt, and combustibles (*8*). When the raw refuse is incinerated directly to recover the heat content, highly corrosive slags are produced, which attack the heat transfer surfaces. Incineration slags are very complex and contain nearly all the elements of the periodic table, the primary constituents being silica, alumina, iron oxides, and calcium oxides, with lesser amounts of titania and magnesia. The mixture is highly variable from incinerator to incinerator, so it will be particularly difficult to develop refractory materials that can universally withstand the particularly destructive environments in waste combustion units.

It will generally be desirable to separate the noncombustible materials before combustion or pyrolytic conversion to fuel for three reasons: (i) to recover the economic value of the metals and glasses, (ii) to recover the considerable energy investment

in originally producing the metals and glasses in the waste (estimated to be 1 percent of the national energy consumption), and (iii) to minimize the slag corrosion problem in the combustor or reactor. The separation procedures involve shredding, screening, air classification, magnetic and eddy current separation, gravity separation, and flotation. The shredders used to comminute the municipal wastes are subject to considerable wear from the abrasive action of the refuse. Because of this gradual wear, the characteristics of the shredded product change, giving rise to difficulties in classifying, feeding, and burning the material. Therefore, development of better abrasion-resistant materials for shredders would accelerate exploitation of this important energy resource.

High-temperature turbines. The efficiency of a gas turbine in converting the energy content of the gas to mechanical motion is limited by the input temperature. Since ceramic materials are inherently tolerant to high temperatures, they could contribute to the development of turbines of higher efficiency. One problem lies in demonstrating long life of ceramic turbine blades when subjected to the repeated temperature shocks of start-ups and continuing centrifugal stress. Since a life of 30 years is the norm for large electric generating equipment, life predictions must be based on an understanding of pertinent degradation mechanisms and on accelerated tests that can be correlated to operating conditions.

Experimental work in a joint government-industry program has demonstrated that silicon nitride ceramic blades can operate at a temperature of 1650°K (2500°F) without cooling (*9*) so that, combined with a second stage of conventional steam, the overall combined cycle efficiency can be 49 percent. Developing the ceramic blades to a commercial level will, however, require considerable additional effort. We lack knowledge and experience in the design criteria for such applications of brittle materials. Designing with ceramics is in no respect similar to designing with metals. A whole new field of knowledge and practice must be developed to deal with problems such as failure mechanisms, creep, and fatigue over long periods at high temperatures and stresses. In addition, forming and rapid machining processes for the ceramics will require development.

In the meantime, metallic alloys are being pushed toward 1370°K (2000°F) by internal cooling and composite strengthening (*10*).

Geothermal. Present commercial production of electricity from geothermal sources in the United States is limited to the Geysers field near San Francisco where dry steam (steam vapor containing no free water particles) is available (*11*). Such sources are limited, and any substantial contribution to the energy program must come from liquid-dominated geothermal fields, or from high-temperature dry rock or magma in which water is circulated from the surface. In either case, hot and extremely corrosive liquid must be dealt with. The largest proved resource in this country is near the Salton Sea in California, but the liquid-dominated fields there have a salinity content up to 25 percent by weight compared to 3.5 percent for seawater. The Salton Sea brine also contains chlorides of 13 other elements. When it is fed directly to a turbine, scale is deposited on iron surfaces of the well head, steam pipes, separators, and turbines; corrosion attacks turbine nozzles, blades, and shaft seals; turbine blades are eroded by fine rock dust blown from the well in quantities that exceed the collecting power of the separator; and on iron parts, coatings are formed composed of iron oxide silica and magnesia. Candidate materials that resist corrosion by brines are high-purity, low-glass ceramics, tantalum, titanium, and perhaps zirconium and plastics. Known for high-temperature resistance and hydrolytic stability are polytetrafluorethylene (Teflon), poly(phenylene sulfide), and poly(phenylene oxide). Other potentially useful plastics are polybenzimidazoles and polyquinoxalines, but few data are available on their hydrolytic stability. It is likely that considerable materials development will need to be accomplished along these lines before recovery of geothermal energy is practical on a large scale. The potential, however, is for as much as 5 quads per year from the Salton Sea area.

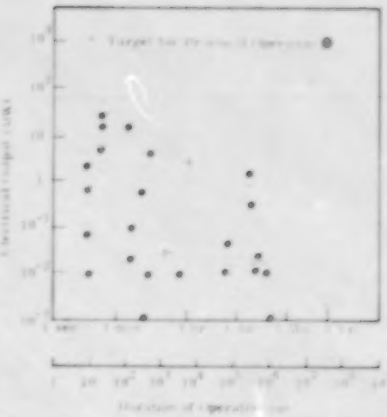

Fig. 3. Output electric power as a function of test duration for open-cycle MHD units using clean fuel (*17*). Operating time was limited principally by materials properties.

Midterm—1990 to 2005

During this period, additional technologies may start to make significant contributions to our energy program. Two represent essentially new resources; the others are concerned with processing of energy.

Fast breeder reactors. The liquid metal fast breeder reactors will operate at a much higher flux (10^{16} compared to 10^{13} neutrons per square centimeter per second in a thermal reactor). This high, fast flux produces many voids in metals, which in simulation experiments cause about 20 percent swelling (*12*). Such swelling would require the design of greater spacing between fuel pins to maintain coolant flow. But since high density of fuel is of first importance to the breeding ratio, to hold swelling to a few percent it will be necessary to develop ways to force recombination of the vacancies and interstitials formed by neutron knock-ons before the vacancies can migrate and cluster to form a void. This might be accomplished by alloying or doping with an element, such as a rare earth, which forms active sites for recombination through trapping of interstitial atoms. Considerably more fundamental understanding of the mechanisms will be needed to accomplish this goal.

Photovoltaic conversion of solar energy to electricity. The silicon solar cell, a derivative of the early transistor work at the Bell Telephone Laboratories, has proved its merit on many space flights, where it is the prime electrical power source. A fraction of the incident optical energy, typically 10 to 12 percent, is converted directly to electrical energy. For large-scale application in the U.S. energy economy, the problem is entirely one of cost (*3*). Solar cell arrays now cost $20,000 to $80,000 per peak kilowatt compared with approximately $500 per kilowatt for conventional steam electric generators (which, of course, require fuel). Cost reduction of two orders of magnitude calls for revolutionary approaches to the system design, the materials, and the methods of manufacturing. One approach is to replace the silicon single-crystal cell with a material or materials that have the appropriate semiconducting properties and yet can be deposited as thin films with suitable properties. Materials of this type that have been actively studied include CdS and CdTe. The most advanced thin-film solar cell is the $CdS : Cu_2S$ heterojunction. It can be fabricated in a manner amenable to large-scale production techniques. Neither this cell nor the variety of other homo- and heterojunction thin-film cells CuInSe$_2$ is nearly as well understood as single-crystal silicon

Table 1. Operating conditions envisaged for the first-wall components of fusion reactors, based on a wall loading of 1 Mw/m². Data are from (*16*, p. S9).

Parameter	Value
Temperature (°K)	600 to 1300 (steady state) ΔT = 50 to 300 (thermal pulse)
Neutron exposure (neutrons per square centimeter per year)	10^{21} (14.1 Mev) 10^{22} (total)
Damage rate (displacements per atom per second)	10^{-6} to 10^{-7}
Gas generation rates (atomic parts per million per year)	75 to 500 (hydrogen) 30 to 600 (helium)
Stress levels (megapascals)	10 to 100
Cycles per year, excluding mirror machines	6×10^{7} to 3×10^{8}

cells, so considerable work will be required before we can determine whether this is the most promising way to achieve direct solar electric power. Availability of materials such as cadmium and gallium must also be established.

Since silicon is so thoroughly understood, some feel that it represents the most promising route to success. New preparation and processing techniques (such as growing long ribbons of single-crystal silicon) may reduce the basic material cost by an order of magnitude. Other processing refinements and the economy of scale associated with very large production quantities can further reduce costs. With optical focusing systems to concentrate sunlight onto the cell so that it is, in effect, working harder, fewer cells will be needed to produce the same amount of electricity.

For any of the solar energy methods—photovoltaic, wind, ocean thermal gradient, space heating, or water heating—systems with lifetimes of 25 years or more are required. It will be difficult to provide materials that operate that long in the natural environment.

Magnetohydrodynamic (MHD) conversion of coal. Magnetohydrodynamics offers a way to convert the energy in coal to electricity without rotating machinery (*13*). In principle, an easily ionized element such as potassium or cesium is seeded into the gaseous combustion products to provide good electrical conduction. The fast-flowing, high-temperature gas is channeled into an intense (~ 5 tesla) magnetic field with electrodes at right angles to the field. The Lorentz force on the moving conductor generates a voltage on the electrode, allowing electric energy to be extracted. If the goals for an operating temperature of 2500°K can be met, an MHD system followed by a conventional steam cycle is estimated to achieve 50 percent efficiency.

No materials are known that can withstand the environment for very long. Figure 3 shows the limited operating times that had been achieved up to June 1975 with clean fuels in MHD test configurations. Economic operation will require at least 20 times the power levels and 20 times the duration of operation achieved in these tests. Moreover, coal combustion gas will coat all surfaces with slag, the uncombustible content present in all coal. Oxides of iron, aluminum, and silicon are the main components of slag; in combination with the seed they react with surfaces in ways that have not been measured, let alone understood.

Development of the electrode material alone will be a major task. The electrical resistivity should be less than 0.01 ohm-meter and relatively independent of temperature. It must withstand mechanical and electrochemical erosion while sustaining heat fluxes of 1.5×10^{6} to 3×10^{6} watt/m² (0.5×10^{6} to 1.0×10^{6} Btu's per hour per square foot), comparable to the heat fluxes at the side of a reentry vehicle. The electrode material should have no phase change up to 2100°K and low chemical reactivity with oxygen or the seed-slag mixture.

In early work in this country metal electrodes (copper or Inconel) have been used at modest temperatures with resultant lower efficiencies. Russian workers have reported encouraging results with electrodes made of the borides of titanium, zirconium, niobium, and alloys of these (*14*). For the future, lanthanum chromic oxide or mixed chromates, or zirconia or zirconia-ceria mixtures, hold promise because of their high-temperature properties, chemical inertness, and low specific resistivity.

Storage. Effective and economic means of storing electric energy are desirable for several reasons. First, intermittent sources such as sunlight or wind become more attractive with good storage methods. Second, the large day-night fluctuation of energy use could be leveled so that the least efficient and most fuel-expensive generating equipment could be eliminated. And third, some energy consumption (such as for personal transportation) could be shifted from petroleum-based fuel to electricity, which could be supplied from coal or nuclear sources.

The only device under active consideration for storing electric energy in its own form is a superconducting solenoid (*15*). Since efficiency can only be achieved at large scale, experimental development costs have been large, and the program has not yet caught the imagination of any funding organization. Other methods of storing electric energy depend on first transforming it to some other form of energy. Most practical is the pumping of water uphill into a reservoir at night and recapturing the stored energy by having it flow downhill during the day. The number of reservoir sites near areas of large energy consumption is limited, however, and lakeside residents may not always accept a lake whose level changes several meters each day.

Electrical energy is traditionally stored as electrochemical energy. Lead acid batteries are in large production and are reasonably inexpensive, but they do not store sufficient energy per unit weight to be used for personal vehicle propulsion. Nor do they attain the long life and large number of charge-discharge cycles needed for load leveling at central plants. Another disadvantage for either application is the inability of the lead storage battery to sustain repeated deep discharges. The nickel-iron battery, developed by Thomas Edison in 1901, has excellent properties, including long life and many discharge cycles, but it is too expensive for large-scale application. The same is true of silver-zinc or nickel-cadmium batteries.

A large impact on the overall national energy program will probably be achieved only through development of completely new battery systems, and those in turn are almost entirely dependent on materials developments. A number of electrochemical systems are under intensive investigation to satisfy stringent new requirements for batteries. These include a lithium-sulfur couple with a molten salt electrolyte, sodium-sulfur with a solid ceramic (beta eucryptite) electrolyte, and lithium chlorine with a molten salt electrolyte. For each of these not only is a whole new technology required, but serious materials problems arise in constructing the battery cells. The positive electrode and its attachment to the current collector suffer a high (oxidizing) potential, which is aggravated by elevated temperatures and any solid oxide electrolytes present. A new material is required that will adequately withstand this destructive environment. The terminals that carry the current through the cell wall must be insulated, and an impervious ceramic material must be developed which is sufficiently resistant to corrosion by the electrolyte.

The allowable cost of the raw material

used to fabricate such a battery makes the materials development program truly formidable. A simple calculation shows that the materials can cost the manufacturer no more than 30 cents per pound if the specific energy density is 40 watt-hours per pound, a reasonable goal (*2*). Thus, any material used in quantity in the battery must be readily available at low cost.

Flywheels provide an alternate method for storing electric energy for load leveling or transportation. The critical material parameter is the ratio of strength to weight. Composite materials with fibers such as Kevlar in modified epoxy have strength-to-weight ratios four times that of high-strength steel. The principal problem will be developing adequate two-dimensional strength for practical wheel configurations.

Long Term—2005 and Beyond

Great hope is being placed in controlled fusion—that is, the nuclear reaction of hydrogen isotopes—to furnish the largest portion of the energy that we will need in the long term. The three principal approaches, in order of funding support, are magnetic confinement, laser fusion, and electron beam fusion. Each is incredibly difficult and beyond the level of technology yet achieved in any other program. Each depends in a critical way on the development of new materials, new concepts, and a deeper understanding of physical phenomena. Materials problems pervade all the programs, but the problem of the first-wall material in a controlled thermonuclear reaction will suffice to dramatically illustrate the challenge (*16*).

The reacting plasma at 100 to 500 MK must be contained in a vacuum envelope, the inner surface of which, closest to the plasma, is referred to as the first wall. The formidable environment at the wall is defined in Table 1. The first problem is to prevent material leaving the wall, which will poison the plasma. A surface element of low atomic number (such as beryllium) may be required. In addition, three points should be emphasized. (i) There is a high flux of 14.1-Mev neutrons from the deuterium-tritium reaction. The only available experimental results obtained at similar fluxes are from fission spectrum neutrons. High-intensity sources of 14-Mev neutrons have not yet been developed for test and evaluation purposes. (ii) At these fluxes every atom will theoretically be displaced more than ten times a year, yet the original mechanical properties must be maintained. (iii) Large amounts of soluble and insoluble gas will be generated in the bulk material, leading to a loss of ductility; this is further aggravated by the irradiation.

Several candidate materials are being investigated. More data are available on the austenitic stainless steels than on any other materials, including measurements of the influence of fission neutrons on their stress-rupture ductility. The stress-rupture life of steel is strongly reduced at temperatures above 550°C because of helium bubble formation and accumulation at internal surfaces such as grain boundaries (*16*, p. S8). The chromium in stainless steel has a high vapor pressure, and sputtering rates may be a problem under the intense bombardment of ions and neutral particles. Nevertheless, stainless steel is the likely candidate for first-wall designs, at least in the early development reactors.

The refractory metals—vanadium, niobium, and molybdenum—are promising first-wall candidates because of their structural strength and low vapor pressure at high temperatures. Because these three metals show loss of ductility due to helium gas bubble accumulation and neutron irradiation, alloys with titanium, zirconium, or chromium are more likely candidates. Whatever the alloy, it must withstand repeated stress cycling in the presence of intense irradiation, which produces voids, hydrogen, helium, and transmutation elements such as zirconium from niobium or chromium from vanadium. Experimental data will not be available until there is a new generation of neutron test facilities.

Magnitude of the Problem

This brief description of some of the materials problems in the energy program may leave some readers with the impression that each problem can be solved when necessary by a hard-hitting effort by one or two companies, perhaps with the support of a government laboratory. Don't believe it! These materials problems are as challenging as any we have ever faced, even allowing for the increased sophistication of materials science. A large, high-technology industry has increased the working temperature of the turbine blade 10°C per year, but for practical magnetohydrodynamics increases of hundreds of degrees are needed in the operating temperatures of materials. The transistor and its progeny did not dominate the electronics market until dozens of universities had formed solid-state research groups to understand silicon in exquisite detail, and if a different material such as CdS : Cu_2S is to be used for photovoltaics, a similar broad effort will be required. To prepare for the era of nuclear power plants, this country has wisely supported for almost 20 years extensive studies on radiation effects in materials at universities and national laboratories. Since problems accompanying controlled thermonuclear reactions are far worse, a correspondingly greater understanding of and experience with the interaction of nuclear radiation with matter is needed before even demonstration models can exploit future successes in laboratory experiments.

To meet the diverse materials needs of the energy program, we will need substantial and sustained effort from universities, industrial organizations, and government laboratories guided by close interplay with energy system designers.

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Forest Resources: An Overview

J. S. Bethel and G. F. Schreuder

A growing concern for the long-term availability of nonrenewable resources has directed increased attention to the feasibility of their substitution by renewable resources. Proposals for direct substitution of renewable resources from farm and forest residues and energy plantations for fuels and chemical feedstocks have been vigorously advanced. This article will deal mainly with forest products, which represent about 98 percent of the tonnage of renewable materials currently used in the United States.

Wood and wood products have some advantages with respect to other materials. One is that when used as structural materials they provide energy conservation opportunities. Cliff (*1*) reported: "Only 453 kilowatt-hours of electrical energy are required to manufacture a ton of lumber. A ton of steel by way of comparison, requires 3780 kilowatt-hours and a ton of aluminum 20,160 kilowatt-hours." In a recent study (*2*), the Committee of the Survey of Materials Science and Engineering of the National Academy of Sciences concluded: "Considerable scope exists for expanding the range of materials obtained from renewable resources. Wood and vegetable fibers might become important sources of primary organic chemicals, although they are not economically competitive today." And the National Commission on Materials Policy, in its final report (*3*), concluded with respect to renewable materials: "They grow on the land, are visible, and need not be discovered, except as species are improved and new varieties are developed by genetic experiments and studies. Reserves grow as photosynthesis combines the energy of the sun with carbon dioxide in the atmosphere to produce vegetative materials. Under management, this supply can be perpetuated indefinitely and even, with improved technology, dramatically increased."

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Supply

A condition precedent to any major effort to substitute domestic renewable materials for foreign nonrenewable materials is an assessment of the available reserves of renewable materials and the potential for replenishment of these reserves after use. The United States is currently a net importer of wood, the principal renewable material. If we were already using our renewable materials to capacity, any effort to encourage substitution would be trivial.

The McSweeney-McNary Act (*4*) of 1928 called for the maintenance by the Secretary of Agriculture of a current census of forest land and its products, an analysis of national supply-demand relationships with respect to forest products, and instructions to suggest methods of achieving a balanced timber budget. The national forest survey is the department's response to this mandate. A general summary of this survey is published at approximately 10-year intervals. It is the only inventory of its kind available in this country, and has provided the factual basis for essentially all national, regional, and state reviews of timber supply. The forest survey as published by the U.S. Forest Service confounds the census and analytical functions in that it is difficult if not impossible for independent analysts to utilize and separately interpret the census information. The most recent version of the national forest survey (*5*) reported the status of American forests in 1970. Its conclusions concerning the future prospects for timber supply have been rather widely challenged. Since it is not feasible to maintain more than one such extensive inventory, it would be desirable to report the forest census data independent of the assumptions made by the department in preparing its analysis. Reporting the census in terms of whole tree volume would permit alternative analyses of materials supply and productivity from the same data base. The technological assumptions then would become part of each analysis, and successive census reports could be validly compared.

The survey could be improved in precision by more intensive use of modern aerial photo techniques and Earth Resource Technology Satellite imagery, combined with advanced sampling techniques. It would be advantageous to use the oncoming change to the metric system as an opportunity to institute change in survey mensuration.

The renewable materials system starts with land. The forest land base and estimates of its productivity are discussed in the following article by Spurr and Vaux. Here the discussion is confined to several problems of forest land classification and management. These problems may distort the estimates of timber resources, and at the same time they reflect deficiencies in national policy with regard to proper management of forest resources.

Given the amount of forest land currently classified as commercial, it is probably unimportant that the criteria for elimination of one-third of the nation's forest land from the materials production base are extremely arbitrary. The commercial production threshold of 20 cubic feet per acre per year probably reflects the nation's timber affluence. In many parts of the world, land well below this production level is managed for timber production. Some of the Alaska land excluded for accessibility reasons should be accessible in the future and indeed the development of the trans-Alaska oil pipeline has probably made some of it accessible already.

Perhaps the most serious questions concerning forest land classification criteria relate not to exclusions from the commercial materials base but to areas included in that base. According to the President's Advisory Panel on Timber and the Environment (PAPTE) (*6*), 18 percent of the commercial forest land in the United States is in the national forests. On the basis of timber productivity, one-third of this land is classified as site III (85 to 120 cubic feet per acre per year) and better. It is not clear how much of this land is available primarily for materials production. The Forest Service is under legal mandate to manage its land in accordance with the multiple use land use principle. Increasingly this mandate is being interpreted to give priority to nontimber uses. Recent court rulings invoking an extremely restrictive interpretation of the Organic Act of 1897 with respect to certain eastern forests and large national forest lands in Alaska move the Forest Service back to its custodial role at the turn of the century. If this type of management mandate is extended to the vast western federal forest holdings, it is doubtful that they can continue to play a significant role as commercial forest land. In large areas of federal forest land recreation and amenity values have been specified as dominant uses

← *Courtesy U.S. Department of Agriculture, Washington, D.C.*

by the federal government, and materials supply is so restricted that its value as a significant materials supply base is doubtful. This is not a phenomenon unique to the United States. The British scientist, S. D. Richardson, has noted (*7*):

> In many countries of the developed world, the traditional wood production orientation of forest managers is being increasingly questioned. In the smaller countries of Europe (e.g., Holland and Denmark) forests are now managed primarily for recreation, with the harvesting of cellulose a by-product of decreasing importance; in North America, that opiate of the forestry profession—multiple use—is being given real substance, partly by pressures generated by the Sierra Club, and the Environmental Defense Fund, and other conservation lobbies.

There has not been a clear designation of national forest lands for which materials production is specified as the principal use with the same legal force associated with wilderness, wildlife, and recreation designations. The Public Land Law Review Commission (PLLRC) made such a recommendation (*8*), but it has not been implemented by Congress. Investments in timber production on national forest lands have been far below those on comparable industrial forest land. Productivity on these lands is further reduced by maintenance of overmature inventories and by lack of prompt reforestation. This apparently reflects decisions to emphasize other uses at the expense of materials supply. Clearly this is a legitimate position with respect to public land use if it is responsive to the body politic. Just as clearly it represents a major, if indirect and perhaps unintended, expression of national policy for materials supply. Given the time required for planning and implementing timber production, it is questionable to continue to assume that the national forests are likely to be significant reservoirs of materials supply in the absence of any clear designation of principal purpose in this domain.

A similar situation exists in the case of nonindustrial forest land. PAPTE (*6*) indicates that 59 percent of the area of commercial forest land is in nonindustrial private ownership. Of this area 32 percent is classified as site III or more productive. Little is known quantitatively about the objectives of these owners. A few are apparently interested in intensively managing their forests, but for the most part this land is being held for ultimate conversion to nonforest use, for speculation, or for its recreation value as a private park or hunting or fishing preserve, and these largely nonconsumptive uses are increasing. Some owners will sell timber if the price is high or if they need partial liquidation of capital. Although long-term management agreements with industrial forest owners have effectively moved other acreages into the intensively managed industrial base, and although public subsidies in a variety of forms has increased the level of management on some areas, these efforts have seriously impacted only a small fraction of the land in this ownership category. Increasing governmental restrictions in the form of forest practices acts and environmental monitoring discourage the nonindustrial owner of small forest holdings from attempting to practice forestry. The industrial forest owner can employ the professional talent required to achieve compliance with complicated regulations. The owner of small properties may be discouraged from trying to practice any forestry other than an occasional harvest from a natural forest stand.

Doubling the output of U.S. forest products over the next few decades is feasible (*6*), but it must be based upon a much more realistic assessment of the stability of the nation's forest system as a timber supply base and a more detailed classification of nonindustrial private forest land based upon some census of owner objectives. The present forest survey information is deficient in these respects. If it is in the national interest to increase the supply of domestically produced wood as a renewable material, there are a number of actions that might be taken by government at either state or federal level. The federal government could undertake to exchange federal forest land for industrial forest land to place a larger fraction of site III and better forest land in industrial ownership for intensive management and a larger fraction of less productive forest land in federal ownership. This would place the most productive land in the hands of those who have the incentive and resources required to take advantage of its productive potential and increase the area of federally owned forest land for dedication to nonmaterials use. The Congress can insist that the federal forest land most suitable for material production be dedicated to that purpose with the same rigorous legal protection now afforded to wilderness areas, primitive areas, wildlife preserves, and recreation areas, as recommended by the PLLRC (*8*). The states can provide incentives through their taxing, zoning, or regulatory functions for the small private forest owner to engage in some forestry practices other than harvesting.

In addition to the land area, estimates of yield from this land base are required in the assessment of materials supply. These estimates involve the measurement of the vegetation in terms of number of trees, volume, growth, and mortality, as well as certain hydrological and economic assumptions concerning the allocation of trees to products and the yield in terms of particular products produced from the trees or tree components. These technological and economic assumptions concern minimum usable sizes and top diameters of trees, different lumber yields obtainable from stem sizes, the product mix to be produced, and many other factors. Many of these assumptions of product yields are based on measures (such as the different board foot measures) or on technological conditions which are of ancient vintage and which generally do not reflect present and future economic and technological conditions and opportunities. Good or bad, these assumptions should be part of the analysis of the census and not of the census itself.

Substitution

The history of the use of substances as industrial materials is replete with substitution among substances. There are very few industrial materials for which another material is not technically substitutable. Furthermore, there are few industrial materials for which there is only one substitution option.

The necessity to abruptly consider substitution of one industrial material for another arose most recently with the oil embargo. It may be desirable to search for long-term alternatives to petroleum as an energy source or as a raw material. Wood has a long history of use as a fuel and clearly could be used again. However, harvested wood is presently used for other purposes, and in the case of residue left in the forest is expensive to collect and deliver to fuel consumption sites. The same problems exist with some of the other potential petroleum substitutes. Thus a decision to divert a renewable material to use as a fuel could result in a supply shortage or an increase in supply cost in the system currently using such a material.

The material system is quite complex in view of the availability of many natural sources, both renewable and nonrenewable. What is needed is a framework that incorporates the diverse information on the technical, economic, energy, and environmental aspects of the materials system and thus facilitates the study of the future role of the renewables as a source of materials and more specifically addresses the substitutions of renewable materials for nonrenewables in particular end uses. The Committee on Renewable Resources for Industrial Materials (CORRIM) of NAS used the concept of a reference materials system (RMS) originally employed by Brookhaven National Laboratory to define the use of energy in the economy. Dr. K. Hoffman of Brookhaven and his associates provided the leadership in CORRIM in the adaptation of RMS to the ma-

terials substitution problem. The analysis illustrated here emerged from part of the work of the CORRIM systems panel.

The RMS is a network representation of the physical flow of materials through all the production and shipment steps required to produce and convert that resource to a form that may be used for a specific purpose in the economy. These steps are referred to as "activities." The renewable resources included in the system are hardwood and softwood forests, minor forest products, agricultural crops and residues, and livestock. Nonrenewable resources introduced for comparison purposes are steel, aluminum, cement and concrete, glass, crude oil, natural gas, and coal. End uses are printing and publishing, packaging and containers, fibers and woven fabrics, nonwoven fabrics, building construction and its various components, durable goods transportation, chemicals, electric power, and fuels. Activities are production or growing, harvesting or extraction, processing, transport (including aggregated shipments throughout all the flow stages), fabrication in primary form, installation, erection, maintenance, and recycling.

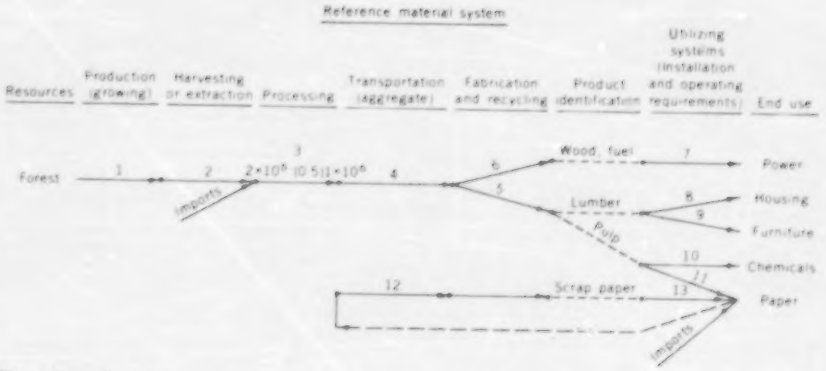

Fig. 1. Sample trajectory subsystem for forest products. The numbers under 3 denote mass flow input (2×10^6), loss factor (0.5), and mass flow output (1×10^6).

The completed RMS shows the flow of materials from the resource through all of the activities to a specific end use for a specific year in a path called "trajectory." Figure 1 is an example of one of the many trajectories developed by CORRIM. Individual trajectories have been developed for renewable as well as for nonrenewable resources, such as hardwoods, softwoods, glass, and steel. Initial trajectories are developed at the very detailed subsystem level and then aggregated into an overview of the whole materials system. Depending on whether the RMS format is to be used as a framework for organizing the diverse technical and economic information on energy, labor, or capital requirements, the number to be substituted for the numbers along the trajectory will portray energy, labor, or capital requirements or just simply the mass flow and material losses through the activities. Such substitutions are shown under 3 in Fig. 1. Energy, capital, and labor requirements can be portrayed as aggregates or can be converted to unit requirements on the basis of either a unit of material throughout for each activity or a unit of the final product. Regardless of the level or kind of detail portrayed, the RMS network can be used for overview and display purposes or as a tool for the analysis of policy alternatives.

The RMS is used for the analysis of materials utilization and substitution by the technique of perturbation analysis. It reflects current and projected use patterns; little by way of dramatic change is assumed in the role of renewables. Depending on the details of the analysis to be performed, the RMS's may be used at the level of aggregation or at the more detailed level of the subsystem. The technique of perturbation analysis involves examination of the specific end use projected in a utilization or substitution problem and definition of any new processes to be used in the affected trajectory from resource to end use. It provides for revision of flows through the affected trajectories in the RMS to reflect changed utilization or substitution of materials, new processes, or both. Finally, it accumulates and tabulates resource, energy, labor, capital, and environmental consequences of the utilization or substitution.

The definition of the technical characteristics of new processes must be done outside the RMS. The intent of the RMS format is to capture those characteristics of the technology that are important to materials policy. Frequently, such technical detail is overlooked in policy formulation because it is not available in a consistent and comprehensive format.

The perturbation of the appropriate trajectories and the accumulation of information on detailed consequences is straightforward with the RMS. When used in this fashion, the RMS can be a useful technique for the analysis of materials policy. It must be recognized that the technique focuses on the physical structure of the system and its requirements. Thus, substitution analysis may be performed in a rather direct manner, but in cases of more general policy analysis, the effects of a policy action on the supply or demand for materials used and on the physical structure of the system must be developed or estimated prior to use of the RMS.

Efforts to construct and utilize the RMS to evaluate potential substitutions within the domain of renewable resources and between renewable and nonrenewable resources clearly indicated the need for a better information base as a condition precedent to the establishment of a national policy for materials in general and renewable materials specifically. Some of the deficiencies in the information base have already been referred to in the discussion of the national forest survey. There are similar deficiencies in the technology area.

Increases in the resource base can be achieved through study of materials improvement and conservation. The study in wood science and technology has been declining in the past 20 years. Most of the federal research investment in this area is directed toward the U.S. Forest Products Laboratory in Madison, Wisconsin. Its research program has been reduced in size, and its efforts in basic research in materials science have been curtailed. Among the universities, several significant programs in wood science and technology have been phased out presumably in economy moves. There are only eight major universities still pursuing important materials research and education in the field of wood science and technology. Accordingly, there is a shortage of scientific and technical manpower in this field. A similar attrition has occurred with respect to research on renewable materials of agricultural origin. In contrast, the federal government has recognized the need for massive levels of research in the nonrenewable resource and energy fields. Finally, little progress has been made in changing building codes; this could lead to substantial materials conservation.

World Trade

The United States, originally a supplier of wood to the world, has been a net importer of wood since 1914. It continues to be a net importer and at the same time maintains a relatively inefficient forest production system in terms of achieving anything like its forest-based materials potential. While the U.S. potential in forest-based materials has been great, its supply of concentrated and cheaply exploitable nonrenewable resources has also been

Table 1. U.S. trade in wood products, 1971. Data are given as roundwood equivalents (10^6 cubic feet). [Source (6)]

Item	Imports	Exports	Net imports
Lumber			
Softwood	1,233	159	1,074
Hardwood	58	26	32
Plywood			
Softwood		10	10
Hardwood	181	1	180
Veneer, hardwood	35	9	26
Pulpwood	95	118	23
Pulp			
Alpha and dissolving	51	127	76
Bleached sulfate	377	170	207
Other	86	31	55
Newsprint and other paper	649	50	599
Paperboard	2	159	157
Building boards	19	4	15
Sawlogs			
Softwood	10	381	371
Hardwood	5	10	5
Total	2,801	1,255	1,546

great. As the most readily and inexpensively accessible supply of these renewable resources became limiting, it was cheaper to seek inexpensive foreign sources of nonrenewable materials than to create the technology required to shift to domestically available sources of alternative renewable resources. The United States has had some self-imposed restrictions on the use of its forest-based renewable resources that encouraged this trend. Its most productive forest land is located in the Southeast and the Northwest. Its greatest population densities are in the Northeast, the Southwest, and the northern Midwest. Movement of its forest-based material resource from production centers to consumption centers requires an effective and inexpensive transportation infrastructure. The nation's long-haul railroad transportation system, originally imaginative in its development, has degenerated in the past 30 years. The federally regulated railroad rate structure has not encouraged long-haul transportation of wood. Alternative water transportation of wood from production site to consumption site has been inhibited by the Jones Act, which requires that ships carrying goods between U.S. ports be under the U.S. flag. The increased shipping costs caused by this legal restriction have essentially eliminated what was once a flourishing intercoastal waterborne timber trade. It has effectively denied to the markets of the contiguous 48 states, on an economic basis, the materials of the forests of Alaska.

Federal legislation implies that it is national policy to achieve a balanced wood budget. References to a balanced timber budget in the McSweeney-McNary Act (*4*) suggest such a national policy, although it isn't clear whether these references are to an internally or an externally balanced budget. In any case, since the act was passed in 1928, the country has never achieved a balanced timber budget either internally or externally, nor has it made significant efforts to move toward either type of balance.

From 1914 to 1971, the percentage of national consumption represented by imports increased from 0 to 12.2. The Forest Service estimates that the nation will continue to import and export wood, remaining a net importer. Given the transportation problems that inhibit matching wood production with wood consumption internally, it would seem more feasible to set as a national goal an externally rather than an internally balanced wood budget. Table 1 shows the import-export status of individual forest product commodities for 1972. For hardwoods, of which the United States grows substantially more than it harvests, the only commodity which shows a substantial excess of imports over exports is hardwood veneer and plywood. This is almost the only major item of international trade in wood that cannot be produced in the United States from domestic forest products supply. This country is a net exporter of hardwood logs and hardwood pulp products and a net importer of hardwood lumber, although the balance of trade in each of these commodity items is relatively minor in terms of value and volume.

On the softwood side, the nation is a net exporter of logs and plywood and a net importer of lumber and pulp products. These international trade movements represent economic trade-offs that largely reflect U.S. transportation restrictions. The largest import volume is softwood lumber from Canada in the amount of 1.165×10^9 cubic feet per year (33×10^6 cubic meters per year). This is predominantly Douglas fir from British Columbia moving into the northern markets of the Midwest and East. The other major softwood import item is pulp products from central and eastern Canada. As with softwood lumber, this very largely reflects importation of newsprint, a commodity that is produced in the United States. Preference for imported materials is largely a matter of price.

Logs represent the only major softwood export item. These are shipped from the northwest states—Washington, Oregon, and Alaska—and go almost exclusively to Japan. In 1972 more than 70 percent of these exports were from Washington. Most of the export logs originated from forest lands in private ownership and from state-owned forest lands in Washington. The federal government and the states of Oregon and Alaska have imposed restrictions upon the export of logs originating from government-owned land. This has sometimes resulted in the artifice of splitting logs into large cants to avoid the export restrictions on logs. The Japanese log export market is attractive to Northwest log producers because of the transportation problems associated with movement of lumber and other softwood forest products to major U.S. consuming centers. In the past, Japan has preferred to buy softwood logs rather than finished products for a variety of reasons. The Japanese construction industry uses lumber and timber sizes that are different from standard U.S. lumber sizes, and its lumber industry typically obtains much larger yields from a log than does ours. The Japanese are partial to white woods such as hemlock and the true firs, species that in the United States typically go into lower valued pulp products. Recently, Japan has moved significantly in the direction of adopting the U.S. stud wall construction method, which makes standard U.S. lumber and structural plywood items more acceptable and competitive in the Japanese market. If this trend continues, the potential for the export of products manufactured from West Coast softwood will improve, and current restrictions on the export of softwood in log form will be less significant.

Canada has very large areas of natural softwood stands, principally in British Columbia. These forests carry the large standing volumes typical of virgin forests but, located as they are in the northern portion of the north temperate zone, many of them have low production potential compared to the highly productive forests of the U.S. Southeast or West Coast. Based upon its large timber reserves, Canada is likely to be a major supplier of softwood to the world for many years. It cur-

rently removes only about half of its estimated sustainable harvest and it exports about three-quarters of its production. The United States is its largest customer, but Canada exports significant quantities of wood to Japan and Europe. Historically wood has moved relatively freely across the Canadian U.S. border. However, Canada can be expected to serve as a reservoir of wood for the United States only as long as it perceives this to be its most profitable market. The United States is currently so dependent upon Canada as a source of softwood lumber and newsprint that any major restriction in price or volume could create a major materials supply problem for this country. Canada's relationships with its former commonwealth partners and with the European Common Market may influence the availability and price of Canadian softwood to the United States.

A very large reservoir of softwood timber exists in the Soviet Union. Like Canada, much of its forest land is in the far north, where productivity is likely to be low. Nonetheless, the large quantities of wood in the present natural stands represent a reserve that is apparently being reduced at a low rate. Two features of the large eastern reserve may influence the rate of its use. More than a third of the volume is larch, which is not a preferred softwood species on the world market. Many of the eastern forests are inaccessible, and the Soviet Union has not committed the capital required to open this resource to use. Russia has been an exporter of softwood to Europe. It supplies some wood to Japan; if the eastern forests were opened to exploitation, this would be a logical market. The Soviet Union is not likely to be an important source of softwood for the United States but if it develops its lumber industry, it could become a factor in the world softwood market and thus indirectly influence the U.S. export-import position.

The northern European countries are important producers of softwood and manufacturers of softwood forest products. Most Scandinavian forests are very intensively managed in comparison to U.S. standards. They are not reducing natural overmature forests as is the case in Canada, Russia, and western United States. Because their silviculture and forest management are much more intensive than those of the other major producers of softwoods, they are growing forests at much nearer their biological capacity than are the other major softwood producers. The Scandinavian countries are major exporters of wood products to the rest of Europe and the United States. There is some evidence that their capacity for manufacture exceeds their capacity to grow wood, and they have been aggressively seeking other supplies of softwood raw material recently in the United States and elsewhere.

The United States has been able to buy softwood at reasonable prices from the softwood-exporting countries and has been content to fill out its softwood needs by importing. This places it in a somewhat vulnerable position if foreign sources of softwood were to change their marketing policies and practices in the pattern of the petroleum and natural gas producers. This country has the opportunity to avoid this vulnerability in the long run, but this would require a change in priorities for forest land use, particularly at the federal level, and in those for the development and use of its long-haul transportation systems.

For hardwoods, the world has a large surplus of supply over requirements. About half of the world's standing timber volume is located in the less developed countries of the tropics. The United States is a large importer of tropical hardwoods, although it grows more hardwoods than it uses. As a result, the hardwood growing stock in the United States is increasing rapidly, much of it in nonindustrial ownership and in the form of unmanaged natural stands. This country could easily become self-sufficient in hardwoods.

In the case of both hardwoods and softwoods, a major limiting factor in any effort to increase the share of the U.S. market supplied from U.S. sources would be an inadequacy of manufacturing capacity. In recent years compliance with environmental regulations has sharply reduced growth in domestic conversion capacity. A substantial fraction, perhaps as much as half, of new capital investment in wood conversion plants during the past several years has been in the installation of pollution control equipment that has not added to the production capacity of the country. New mill construction, in the fiber sector, has been inhibited by concern for ability to produce at a profit in the face of uncertainties about government regulation. Several developments in wood technology could foreshadow a change in the general world wood market. Methods are being developed that permit hardwoods to be substituted for softwoods in traditional softwood uses, particularly in the area of pulp and paper manufacture. Some of the new composites, such as structural particleboard, can be produced from hardwood and may be able to compete effectively in the structural timber market where softwoods have traditionally been dominant. Worldwide there is a growing interest in structural plywood produced from hardwoods, which would also provide opportunities for softwood replacement by hardwoods.

In many of the developing countries the trend toward conversion from wood and charcoal to petroleum as a heating fuel may be reversed as a consequence of the increased cost of petroleum. While the conversion of wood residues to liquid and gaseous fuels still seems to be a marginal undertaking in the United States, it has the possibility of being a much more viable enterprise in tropical hardwood-rich countries that do not have the options of large-scale hydroelectric developments, and exploitable oil and coal resources. Many tropical hardwood forests support 4000 to 5000 cubic feet (110 to 140 m^3) of biomass per acre in vegetative cover, but only 1 to 2 percent of this volume is useful in the production of industrial materials. These concentrations of raw material may make the production of liquid and gaseous alternatives to petroleum feasible. Such developments could influence U.S. materials supply problems by reducing the worldwide demand for petroleum, thus easing the U.S. position as it competes in the world market for fossil fuels.

Another development that could ease the future pressure on softwood timber supply is the conversion of native tropical hardwood forests to introduced softwood species. Such conversion has been successful in many temperate zone hardwood areas in Europe, the United States, Australia, New Zealand, Chile, and Argentina. It is much more difficult and costly in the tropical regions of the world but experimentation with this sort of conversion is widespread throughout the tropics. It would probably be much more feasible technically and less expensive to convert more hardwood areas to softwoods in the United States than in the tropics. This is becoming less acceptable from a social standpoint in the industrial countries, where hardwood forests are prized for their recreation and aesthetic values. This attitude has not yet represented a serious restriction in most of the less developed countries of the tropics.

Given the great potential of the tropics in the long-term timber supply picture and the heavy dependence of the United States on foreign wood resources, it is surprising that this country has very largely ignored the opportunities for bilateral cooperative programs with potential wood suppliers in the tropics. Many U.S. based corporations are very active in tropical regions, but the federal government has been inactive. Development of forest resources has never been a strong objective in U.S. foreign assistance programs. Those programs that have been undertaken at the request of foreign countries have been ad hoc, intermittent, and, lacking central planning, often ineffective. This is a mis-

take that is not being made by the other major industrial countries, whether exporters or importers. While most bilateral research, development, and education programs have as their central purpose the advancement of the recipient country, many of the best of these foster the mutual interests of the two countries involved.

Summary

The United States has a large potential capacity for increasing the supply of renewable materials that could substitute for scarce nonrenewables or for renewables in foreign jurisdictions. It has not elected to give high priority to this development. If such a goal were viewed as a desirable national policy, several actions would be indicated. The national forest survey could be improved to provide a better basis for assessment of current reserves and long-term production capacity. Federal and state land use policies could emphasize the importance of encouraging materials production on the most productive forest sites. The research needed to improve product yields from renewable raw materials and to advance cost-effective technologies could be encouraged at government laboratories and in the universities pursuing these lines of research.

Given the possibilities of sudden change in resource price and availability on the world market, it would be prudent for the nation to improve its options for substitution of domestic renewable materials for foreign nonrenewable materials. Rapid substitution is not feasible if the essential foundation in science and technology has not been fostered in advance.

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Timber: Biological and Economic Potential

Stephen H. Spurr and Henry J. Vaux

Forests are estimated to cover 33 percent of the land surface and 10 percent of the total surface of the earth. In terms of the world net primary production, they account for 67 percent of all dry matter production on land and 45 percent of the total produced on both land and water (*1*).

If we define as timber the merchantable stems or boles of trees in the forest at least 5 inches (12.7 centimeters) in diameter at breast height, including all the wood above a 1-foot stump and extending up to a 4-inch top (this is the definition of roundwood used in the forest survey of the U.S. Forest Service) it would appear that approximately half of the total biomass produced by the forest is timber (*2*). Roughly 20 to 25 percent of all photosynthetic matter produced on earth is accounted for by this one product.

From a biological point of view, timber (or more strictly speaking, wood) as a renewable natural resource has great potential. From an economic point of view, however, many factors operate to reduce the use of wood and indeed the use of forested land to produce wood under intensive management. These are the subjects of this article.

The overall biological potential of the forests of the United States can be most simply expressed in terms of the area of land devoted to the growing of trees to be utilized as wood or timber and the average growth of wood per unit area under different intensities of management. The total productive potential is the product of the two. Economic and institutional considerations will determine in large part that portion of the potential forest acreage that will actually be utilized and the degree of management intensity that will in fact be practiced.

Area of U.S. Commercial Forest

One-third of the land area of the United States or 754 million acres (305×10^6 ha) was classified as forest land in 1970 (*3*), of which two-thirds or 500 million acres (202×10^6 ha) is commercial timberland according to the definition established by the U.S. Forest Service. This provides that such lands are capable of growing at least 20 cubic feet of timber per acre per year (1.4 m^3 per hectare per year) and are not legally withdrawn from the possibility of timber harvesting (such as wilderness area) (*4*). The definition is thus in part biological in that it is based upon potential growth per unit area and in part legal in that it excludes productive land legally withdrawn from use. It is in no sense economic, and thus the term "commercial" is a misnomer.

The commercial forest base of 500 million acres will change as a result of additional withdrawals of forest land, clearing of forests to convert land to agricultural use, abandonment of agricultural land to forest use, and clearing of forests to convert land to urban or industrial use.

Some 20 million acres (8×10^6 ha) of productive timberland is currently used for parks, wilderness, and other purposes not compatible with the harvesting of trees for timber. Substantial political pressures currently exist to withdraw additional forested lands from timber production. At present there are some 12.3 million acres (5×10^6 ha) in the National Wilderness Preservation System, 93 percent of which is in the national forests and much of which would not be classified as commercial forest because of the slowness of growth.

The area of formally designated wilder-

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ness will undoubtedly increase. As of July 1975, 112 proposals for additional wilderness covering 26 million acres (10.5×10^6 ha) were before Congress, while 316 other areas totaling in excess of 13 million acres (5×10^6 ha) were under study by the National Park Service and the Forest Service (*4*). Alternative goals being considered for Forest Service's Renewable Resource Program range from a total National Forest Wilderness target of 17.3 to 41.0 million acres (7×10^6 to 17×10^6 ha). If this system were expanded to 28.5 million acres (11.5×10^6 ha), and if half of the withdrawals were from commercial forest land, somewhere in the neighborhood of 8 to 9 million acres (3 to 4 million ha) would be withdrawn from our commercial forest land base. Wilderness designations within the national parks would not affect this base because these lands had already been classified as nonavailable for timber harvesting. On the other hand, there are very real possibilities that additional lands will be purchased by the federal government in the eastern United States for use as national wilderness, adding up to a loss of perhaps 10 million acres. This, added to the 5 million acres in the Rocky Mountains discounted because of inaccessibility (*3*), reduces the effective commercial base forest to 485 million acres (196×10^6 ha).

Marginal lands continue to move from forest to agriculture and vice versa. The Forest Service (*5*) estimates that from 1962 to 1970, 3 million acres (1.2×10^6 ha) of former agricultural land was converted to forest in the mid-Atlantic states while 7 million acres (3×10^6 ha) of forest was cleared, largely for farming, in the South. There, much clearing of commercial timberland for soybean and other crop production has taken place in recent years on the floodplains of the Mississippi and other rivers. In addition, extensive areas of forest upland were converted into pasture. If the net loss of timberland to farming has been approximately 4 million acres in 8 years, we project, over the next five decades, a loss of 20 million acres (8×10^6 ha) of forest, presumably all of it classified currently as commercial timberland.

Finally, in all regions of the United States, sizable areas of forest lands have been lost to suburban development, highways, rights-of-way, reservoirs, and other nontimber uses. We estimate a total loss of 10 million acres from these sources over the next 50 years.

Add these two sources together and we project that the commercial timberland base would be further reduced to 455 million acres (184×10^6 ha) by approximately the year 2020. The comparable U.S. Forest Service projection is 475 million acres by 2020 (*3*). In addition, as discussed below, substantial acreages classified as commercial forest land will not in fact be used to grow timber for commercial use because the owner either does not wish to or cannot profitably manage his land for that purpose.

Expected Changes in Forest Productive Potential

Since the future productivity of the forests of the United States is estimated by multiplying the area of commercial forest land by the expected mean growth or increment per unit of area, the question naturally arises as to the effect that the reduction of the commercial forest area from 495 million acres to 455 million acres will have on the mean productivity of these lands. In its national forest survey (*3*), the U.S. Forest Service recognizes five site classes or productivity classes of land according to the potential mean annual increment of the native forests if they fully occupied the site. More precisely, site is categorized by the mean growth in cubic feet per acre per year at culmination of mean annual increment. Site class I consists of land capable of growing, per year, 165 cubic feet per acre (11.6 m^3/ha) or more; site II, 120 to 165 cubic feet per acre (8.4 to 11.6 m^3/ha); site III, 85 to 120 cubic feet per acre (6.0 to 8.4 m^3/ha); site IV, 50 to 85 cubic feet per acre (3.5 to 6.0 m^3/ha); and site V, 20 to 50 cubic feet per acre (1.4 to 3.5 m^3/ha). Since there is much more poor than good site land, the average potential productivity of the current commercial forest land base is estimated to be 74 cubic feet per acre per year (5.2 m^3 per hectare per year), a figure well within site IV.

Of the 40 million acres estimated to be withdrawn from the commercial forest land base, the 10 million acres withdrawn for wilderness and similar purposes will be predominantly from the lower sites, since the terrain desired for this use, picturesque unroaded land in mountainous and hilly country, generally has relatively low timber growth potential. On the other hand, the 20 million acres estimated to be withdrawn from the commercial forest land base for agricultural purposes will be predominantly from the better sites. They will not be from site I forest lands, for these are primarily located in the Pacific Northwest and are under relatively little pressure for conversion to agricultural land, but they will be from site II and III forest lands in the southern states, much of which are presently covered by bottomland hardwood forest. Withdrawals for nonagricultural use such as for suburban development and rights-of-way will be generally unrelated to site quality. These lands thus are presumed to average near the present mean in terms of forest productivity. The net result of these withdrawals for wilderness and recreation, agriculture, and development thus may be a slight reduction in average productivity of the lands classified as commercial forest in 2020. In our rough model, we assume an average growth in 2020 of 71 cubic feet per acre per year (5.0 m^3 per hectare per year).

Yield of U.S. Commercial Forest

The current net annual growth of the 495 million acres presently classified as commercial forest in the United States is estimated by the U.S. Forest Service (*3*) to be 38 cubic feet per acre (2.7 m^3/ha). Multiplying the mean annual increment by the area to which it applies gives a current estimate of net growth of 18.6 billion cubic feet per year (530×10^6 m^3/year) for the United States as a whole.

Volume data can be approximately converted into dry weight equivalents on the basis of 27.4 pounds per cubic foot (438 kg/m^3) for softwoods (gymnosperms such as pine, spruce, and fir) and 32.8 pounds per cubic foot (525 kg/m^3) for hardwoods (angiosperms such as oak, maple, birch, and aspen). The conversions are based on green volume and oven-dry weight. On the basis of the present mix between hardwoods and softwoods, the conversion factor is 29 pounds per cubic foot (467 kg/m^3) for all species.

In its recent study (*3*), the U.S. Forest Service has projected the growth of forests at 10-year intervals to the year 2020 by assuming a continuation of 1970 levels of forest management (*3*) – that is, that silvicultural treatments of the forest will maintain the levels of the late 1960's in terms of acreage treated and dollars expended. The cultural practices include forest fire control, insect and disease control, planting and natural reforestation, timber stand improvement, fertilization, assistance to private landowners, research, and road construction.

Under these assumptions, the acreage of commercial forest land is projected to drop from 500 million acres (202×10^6 ha) in 1970 to 485 million acres (196×10^6 ha) in 2000. Net growth per acre per year is expected to increase from a present 38 cubic feet per acre (2.7 m^3/ha) to 41 cubic feet per acre (2.9 m^3/ha) by 2000, an increase of 8 percent. The total net growth of the U.S. forests would then rise from a present 18.6 billion cubic feet (530×10^6 m^3) to 19.6 billion cubic feet (555×10^6 m^3) by 2000, an increase of about 5 percent.

Since these projections assume a contin-

uation of 1970 levels of management, it follows that the increased production per acre is presumed to arise from such factors as the conversion of slow-growing old-growth timber to faster-growing young-growth, and from improvement of stocking from continued planting and natural regeneration.

The U.S. Forest Service estimates potential productivity of forest lands through the use of normal yield tables which give the estimated volume of even-aged forest stands that fully occupy the ground at a given age and on a given site quality. On this basis, the potential growth of U.S. commercial forest lands is 74 cubic feet per acre (5.2 m^3/ha), or 95 percent greater than the present average net annual growth.

The normal yield table approach, however, has distinct shortcomings. First, it assumes that forests are managed as even-aged stands and does not adequately assess potential growth of stands managed on an uneven-aged basis. Second, yield tables are often developed from measurements of temporary sample plots which are subjectively chosen as appearing as fully stocked as possible; this introduces an element of bias as well as the possibility that a younger stand so chosen will not necessarily develop into the same dimensions as an older stand. Yield tables do not predict adequately the growth of stands that are stocked less or more than the "normal" plots. Most American normal yield tables do not provide an adequate basis for estimating the growth of managed stands. Managed stand yield tables derived from the repeated measurement of permanent sample plots, are greatly needed to supplant the current yield tables for unmanaged stands derived from data on subjectively chosen temporary sample plots.

The Forest Service estimate that the potential growth of U.S. forests is 95 percent greater than the current growth is also suspect because of the estimation method. Current growth is estimated by stand-table projection methods involving the measurement of the width of growth rings taken through increment cores and correction of gross growth estimates thus obtained to net growth through estimates of future mortality, the latter being a low precision procedure at best. Differences between the growth estimates thus derived and estimates of forest productivity obtained through the use of yield tables may be due in part to differences in methodology.

Nonetheless, we know that potential growth is much greater than current growth. Much of the western commercial forest land is still covered with old-growth forests for which net growth is negligible because the rate of mortality approximates the rate of wood growth in the surviving trees. In addition, over 20 million acres (8×10^6 ha) of our commercial forest lands are currently without trees, and much of the remainder is only partially stocked with trees.

Actual yields over large areas will never reach the level predicted from carefully selected sample plots. Inevitably, holes in the forest canopy will be created by rocky or wet spots on the ground, by the death of occasional trees that cannot be harvested, by the random presence of slow-growing species, and by human occupancy and use. In Sweden, actual yield under intensive management has been estimated at 90 percent of that estimated from yield tables (*5*). Lacking similar data in the United States, we may use this figure for an approximation.

Bearing these limitations in mind, we take 90 percent of our 2020 estimate of 71 cubic feet per acre as our first estimate of the potential net productivity of U.S. forests. For a forest land base of 455 million acres, a growth of 64 cubic feet per acre will yield an annual biological production of 29.1 billion cubic feet per year (820×10^6 m^3/year). This is the estimated growth of stem wood merchantable by current standards if all commercial forest land were fully stocked with an even distribution of age classes, these stands were harvested at the culmination of mean annual increment, and there were no thinning or other cutting in the forest before the final clear-cutting of the even-aged stands. In short, it is a rough estimate of the maximum net growth possible from American forests if they were managed only to be as fully stocked as possible.

Obviously, we have the capability of applying known silvicultural techniques to substantially increase the harvestable growth of our forests. The potential biological productivity of U.S. forests under intensive management has been assessed in broad terms on a countrywide basis (*6*). In this recent study, it was assumed that intensive management would involve practicable but not necessarily economically profitable programs for (i) site improvement through fertilization, drainage, and irrigation; (ii) conversion of existing slow-growing inferior forests to faster-growing forest types; (iii) improvement of stocking through reforestation; (iv) introduction through planting of genetically faster-growing trees; (v) stimulation of growth of desired species through weeding back of competing trees; (vi) recovery of a larger share of the gross growth through thinnings to salvage trees before they die; and (vii) reduction of losses from fire, insects, and diseases through better forest protection.

The gains in forest productivity through the widespread application of the above silvicultural practices are substantial. In terms of percentage increment nationwide, they are summarized as follows.

The practicability of applying nitrogen fertilizers in the Pacific Northwest and of coupling potash fertilization with drainage of wet pinelands in the South has been amply demonstrated. If 10 percent or 50 million acres of commercial forest land can be similarly treated to increase growth by 15 percent, the average growth on all forest lands would be increased by 1.5 percent.

Conversion of existing forests to suitable faster-growing types also would result in increased forest productivity. If we assume that 30 million acres of slower-growing hardwoods were to be converted by clear-cutting and planting with faster-growing southern pines, Douglas fir, and other conifers, and predict an increased yield of 50 percent in such cases, the average net gain would be 3 percent for the commercial forests as a whole.

Major gains from improved genetic selection apply only to species, primarily conifers, that are managed by clear-cutting and planting. If we project that 30 million acres will be converted from hardwoods to softwoods, 20 million acres of nonstocked land will be afforested, growth of Douglas fir and other conifers will continue on 30 million acres in the Pacific Northwest, and growth of southern and eastern pines will continue on 70 million acres, 150 million acres would be available for planting with genetically improved stock. If this conversion were scheduled over a 50-year period, 3 million acres could be so forested each year. With a postulated growth gain of 1 percent per year, the net growth improvement would be 7.5 percent for U.S. forests as a whole.

Intermediate treatments such as weeding to provide adequate growing space for the desired tree species and thinning to salvage trees that would die so as to concentrate the growth on the most desirable stems can be expected to produce harvestable yield increases of 25 percent.

In 1970, the net annual growth of our commercial forests was 18.6 billion cubic feet, or 80 percent of what it would have been were it not for an estimated mortality in the same year of 4.5 billion cubic feet. In its recent report (*3*), the Forest Service projects a continued 20 percent loss from mortality. It seems reasonable that this loss could be reduced to 15 percent with more intensive protection against losses from fire, insects, and disease.

A realistic level of forest productivity

under widespread intensive management can be estimated by beginning with the Forest Service projection for potential growth computed from yield tables and adding or subtracting the following:

Holes in the forest canopy	10	percent
Fertilization and drainage	+ 15	percent
Conversion of forest type	+ 3	percent
Genetic improvement	+ 7.5	percent
Weeding and thinning	+25	percent
Mortality losses	15	percent

The potential growth for 2020 of 71 cubic feet per acre per year would thus be adjusted upward by 7.5 percent ($0.90 \times 1.015 \times 1.03 \times 1.075 \times 1.25 \times 0.85$) to 76 cubic feet per acre per year (5.3 m^3 per hectare per year).

For a commercial forest land base of 455 million acres, therefore, the potential productivity of U.S. forests would be 34.6 billion cubic feet per year (980×10^6 m^3/year). This would be approximately twice the present net growth and two and one-half times the current (1970) net removals of 14 billion cubic feet. This estimate represents the maximum biological productivity of American forests if present levels of silvicultural technology were widely practiced. It could not be attained until approximately 50 years after the initiation of such practices at the levels indicated. Policy and economic considerations to be discussed below will inevitably limit the attainment of this biologically feasible potential.

The estimated nationwide potential net growth of 80 cubic feet per acre of commercial forest land per year is for the merchantable portion of the stem only. Were the stump, top, bark, and branches of the trees in the forest to be utilized at time of harvest as well, the yield of forest products would be increased by approximately 40 percent. Thus the potential yield would be approximately 110 cubic feet per acre per year (8 m^3 per hectare per year), a volume that would produce about 3200 pounds (1450 kg) of biomass dry weight per acre per year.

Restraints on Use of Commercial Forest

We noted above that some forest covered land is excluded from classification as commercial forest either because of low natural productivity or by legal withdrawal. Now some additional economic and institutional restraints on attaining full biological potential must be noted.

The *economic* potential for timber growing is limited by the fact that on sites of lesser productivity the real cost of growing wood may exceed the real value of the wood produced. Where this is the case, whether on public or private land, any expenditure to grow trees will be socially wasteful. Thus, some areas which have significant biological potential for wood production are economically submarginal for such production in the light of prospective conditions of wood demand and supply. Precise identification of the economic margin for timber growing is surrounded by a great deal of uncertainty. Since marginality depends on the market value of an output which will only be marketable after several decades, identification of the margin depends on an estimate of what demand for timber will be a great many years in the future—an estimate beset with uncertainty about future levels of population and income, long-term changes in tastes, technology, the availability of substitutes, and a wide array of other factors.

Despite these uncertainties, both the logic of determining the nation's economic potential for timber growing and the practical necessity of deciding where and when to grow wood requires that future wood markets with all their uncertainties be assessed, albeit with caution. Under congressional directive, the U.S. Forest Service has conducted repeated studies of the outlook [for example, (*3*, *7*)]. In general, these timber-demand projections have stood up well both in comparison with independent analyses of others and, in the case of some of the older efforts, with actual realizations at termination of the forecast period. Thus, use of such projections as a basis for estimating economic potential is warranted, provided one recognizes the uncertainty inherent in them.

The most recent Forest Service study estimates a market for industrial roundwood in the United States in the year 2020 of about 28 billion cubic feet (790×10^6 m^3) if 1970 prices were still to obtain (*5*). This represents a little more than a doubling of demand for wood over the next 50 years. (Since this is a projection of *demand* and since prices of wood are generally expected to rise significantly, it should not be inferred that *consumption* of wood is likely to double.) The price elasticity of long-run demand for wood products has been little studied but seems likely to lie in the range -0.5 to -0.75 (*8*). Using assumptions consistent with this view of the demand outlook, three recent studies have explored the economic potential in various forest situations. Vaux (*9*) found that, with some variations due to species, site productivity class V was submarginal in California, as were the more costly portions of class IV. A comparable conclusion would follow from Clawson's work on the Pacific Northwest and the South (*10*). Similarly, Montgomery *et al.* (*11*) found that with relatively intensive forest plantation management in Georgia, timber-growing investments on site V land would, in most cases, be unlikely to yield returns sufficient to cover costs.

In light of these evaluations, perhaps 15 percent of the aggregate biological potential for wood production (that on site V and low site IV land) is submarginal for economic production at least in relation to a 50-year future time horizon. (This may not mean, however, that all of this 15 percent is lost to society. Most forest land, even if it is of the poorest productivity, and is not under any form of economic timber management, will produce some wood provided only that it receives effective protection against wildfires and pest epidemics. Since such land is likely to receive this kind of protection in order to maintain its nontimber values, a modest fraction of the wood potential from submarginal timber growing land may well be available.) We conclude that the economic potential for wood growth under the management regimes outlined earlier is 29.4 billion cubic feet per year (830×10^6 m^3).

The extent to which this economic potential will be realized depends on the attitudes and intentions of the forest owners and on the institutional environment in which they make their management decisions. There are more than 4 million such owners in the United States (*7*), with widely divergent ownership objectives and substantially differing degrees of managerial effectiveness. Full economic potential is most likely to be realized on lands owned by forest products industries. Land in industry holdings comprises 17 percent of such potential. An additional 25 percent is in various forms of public ownership, two-thirds of which is in the National Forest System. Most public forest land having economic potential for wood production is managed under the multiple use policy, which means that realization of portions of the wood-growing possibilities may be deliberately foregone in order to maintain alternative forest values such as recreation. Any present judgment as to the magnitude of this impact is highly speculative. On a number of western national forests, 40 to 55 percent of the commercial forest land currently is managed for objectives which limit full realization of the economic potential for timber. Due to these constraints from competing land uses, perhaps 75 percent of that potential might be attainable in the future on the public forests.

The bulk of the economic wood-growing potential (58 percent) is on private nonindustrial ownerships. Such ownerships defy generalized description because of wide variations in ownership intents, size

of holding, and managerial skill (12). Forest Service estimates in 1973 indicate that only about 5 percent of these ownerships are intensively managed for timber growing, that about 15 percent are held for purposes generally incompatible with timber growing, and that on the remaining 80 percent wood-growing potential is at present being only partly utilized. The extent to which such utilization may improve in the future will depend largely on economic and institutional factors to be mentioned below. Without future improvement in these factors we would expect farm and miscellaneous ownerships actually to realize little more than the 49 percent of total potential they were achieving in 1970. In the absence, then, of substantial economic and institutional change, practically realizable yields within the 50-year time horizon appear to be constrained to 19.0 billion cubic feet (540×10^6 m^3). Although this figure is more than a third higher than the 1970 levels of removals, it is only two-thirds of the level of consumption to be expected if real prices of wood remain constant. Hence, future continuation of the historic rising trend of real prices of wood is generally expected.

The prospect of such price rises could conceivably lead to fuller realization of economic potential on farm and miscellaneous ownerships, to significant further intensification of management on industrial forests, and to some shift in public forest management objectives toward greater emphasis on timber growing, at least on the better sites. As we have seen, there is room within the constraint of economic marginality to meet the prospective 50-year demand expansion fully, provided price prospects stimulate the necessary timber-growing response. If they do not, actual realization of substantially higher prices will serve to constrain consumption and hold it close to the level of 19 billion cubic feet (540×10^6 m^3). Which of these outcomes is realized will depend largely on what public forest policies are pursued during the next two or three decades and how those policies influence the long-term timber-growing efforts of various classes of forest owners. The possibilities may be suggested by outlining two alternative scenarios from among the innumerable possible ones.

A scenario which assumes continuation of present forest policies would lead to levels of wood consumption at the end of 50 years on the order of 19 billion cubic feet, accompanied by real prices for industrial roundwood at perhaps twice present levels. The social costs of such an outcome would have to be measured both in terms of the resultant higher costs for wood-based consumer goods and in terms of expanded use of wood substitutes. Such substitutes are derived mainly from nonrenewable resources, chiefly metals and plastics. There is at least some evidence that many such substitute materials may have higher energy requirements and have more serious environmental impacts associated with production of a given utility than those associated with production of the same utility from wood. These considerations suggest the wisdom of a forest policy looking toward fuller utilization of the economic wood potential.

A second scenario could result from public policy changes designed to stimulate fuller utilization of existing economic potential for timber growing. More intensive timber management will require large amounts of capital. Forest Service preliminary studies have identified capital investments needed for such intensification ranging from $40 to $80 per acre, with associated increases in yield of 75 to 125 cubic feet per acre treated. Thus, to raise output 50 years hence by 1 billion cubic feet (28×10^6 m^3) would require new timber-growing investment in the near future on the order of $600 million. A major source of underutilization of productive potential on both national forests and farm and miscellaneous ownerships has been lack of an adequate level of capital investment. In the national forest case, the needed appropriations of federal funds simply have not been made. Inefficient size of ownership, meager access to capital, uninsurable risks, and adverse local tax systems are among the significant deterrents to forestry investments on nonindustrial private ownerships. Policy changes in these areas leading to expansion of forestry investment by $2 billion to $3 billion over the next two decades would increase wood yields 50 years hence by 3 billion to 5 billion cubic feet. This would moderate the expected wood price rise to perhaps a 50 percent increase. The social costs of this alternative would be in the form of alternative investment opportunities foregone from commitment of the additional $2 billion to $3 billion to forestry and probably some modest reduction of recreational and amenity values on public lands.

Conclusion

The preceding assessment may be recapitulated in terms of the following estimates:

Biological potential from fully stocked stands, 29.1 billion cubic feet per year (820×10^6 m^3/year).

Biological potential with more intensive management, 34.6 billion cubic feet per year (980×10^6 m^3/year).

Economic potential under more intensive management, 29.4 billion cubic feet per year (830×10^6 m^3/year).

Economic potential under existing institutional constraints, 19.0 billion cubic feet per year (540×10^6 m^3/year).

Future domestic demand for wood falls somewhere between the last two of these estimates. Whether consumption 50 years hence will be close to the higher or to the lower estimate will depend on what forest policies are pursued, particularly over the next two or three decades. Prompt adoption of policies designed to stimulate timber-growing investment on a very substantial scale could result in more moderate increases in wood prices accompanied by future consumption levels in the neighborhood of 28 billion cubic feet (790×10^6 m^3). In the absence of such a stimulus to investment, future consumption is unlikely to exceed 19 billion cubic feet (540×10^6 m^3) with real wood prices double their present level. Achieving the higher of these two levels will involve large capital investments and consequent costs in terms of the other programs foregone plus at least a modest sacrifice of some recreational and amenity values. The lower alternative involves significant social costs in terms of higher prices of wood products to consumers, lower levels of product consumption, and significant substitution of nonrenewable materials (with potentially higher energy requirements) to provide consumer utilities which could, under the alternative policy, be readily supplied by wood.

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Timber: More Effective Utilization

Edwin C. Jahn and Stephen B. Preston

Timber is commonly defined as trees or forested lands that are a source of wood. Timber provides the renewable resource base for the forest-based industry, considered by various measurements as the fifth largest in the United States.

The major products from timber are (i) structural wood products and (ii) fiber products. The first category consists of lumber and rigid panels including plywood, particleboard, flakeboard, fiberboard, and insulating board, which serve in primary forms as building materials and from which innumerable secondary products are made. The fiber products are market pulp, dissolving pulp, paper, paperboard, molded pulp goods, hardboards, and the hundreds of products made from them (*1*). Three other groups of products are or may also be derived from trees, namely, extractive materials (naval stores, oils, drugs, tannin, and other products); chemicals from the woody tissue or lignocellulose (sugars, alcohol, phenols, and others); and energy (wood fuel, bark, pulping by-products, and pyrolytically produced methanol, gases, and charcoal). In this article we shall deal mainly with structural wood products and fiber products, which provide by far most of the end-use materials from our forests.

Structure of the Industry

Some 250 million tons (226 million metric tons) of raw wood—approximately equal to the U.S. annual production of all metals, cements, and plastics—are currently annually processed by the nation's forest products industries. Projections of the U.S. Forest Service predict a doubling of this demand between 1970 and 2000. Currently, approximately 35 percent of the raw material from the forests is converted to fiber-based products, and 63 percent is required for primary structural materials. By the year 2000, fiber-based products are expected to account for approximately 46 percent of the 22.3 billion cubic feet (630 × 10^6 cubic meters) predicted then to be required annually, with structural products accounting for about 50 percent.

Structural Products

For limited structural applications, wood enters the market in its simplest form as a segment of a tree trunk. For use as poles, posts, and piling, processing requirements beyond harvesting are largely limited to removal of bark and often impregnation with preservative chemicals toxic to fungi and insects. Over 85 percent of structural wood, however, is first converted into prisms or sheets as primary products which are used in these forms for such purposes as building construction or, alternatively, manufactured into innumerable secondary products reliant in part for their utility on form and structural integrity.

Basic primary products are lumber, which is sawed or shaped from the log, and rigid panels, fabricated by reducing roundwood to veneer, particles, flakes, strands, or fibers, which are, in turn, reconstituted into thin sheets by pressing between heated platens, usually in combination with an adhesive. Sheets thus formed are plywood, fabricated from veneer, and building board consisting of an array of engineered products generically classified as particleboard, flakeboard, hardboard, and insulating board.

In 1970, approximately 62 percent of the structural wood consumed in the United States entered the market as lumber, 14 percent as plywood, and 11 percent as building board. This product mix is continuously changing, with reconstituted products accounting for increasing percentages of the total, as a result of changes in the size and quality of the forest raw material, modifications in techniques of building construction (which consumes over 50 percent of our structural wood products), and improvements in processing technology.

The diminishing supply of large logs suitable for lumber of large dimensions, and for plywood, the necessity of using an increasingly higher percentage of the forest biomass which has previously been considered forest residue, and the economic desirability of complete utilization of all raw material entering processing combine as strong incentives for the development of new reconstituted structural products as alternatives to lumber and plywood. Products important among those which are technically and economically feasible and can be expected to enter the market soon are lumber laminated from veneer and a variety of designs of reconstituted structural wood. The former, fabricated from veneer unsuitable for plywood, can serve the same function as lumber of large dimensions, but can be used more efficiently in engineered structures because of better control of variability. The latter, reconstituted from strands or flakes generated largely from what is now forest residue or from low-grade hardwood logs (which are in oversupply), can be used as alternatives to lumber or plywood, depending on the design. The use of structural flakeboard for sheathing in building construction—a function now served largely by plywood—is particularly promising.

Fiber Products

The data in Table 1 indicate that the U.S. pulp, paper, and paperboard industry is large by any standard and plays an important role in the nation's economy. This industry has experienced rapid, continuous growth, amounting to an increase in production of almost 3½-fold over the past three decades. Per capita consumption was 618 pounds (278 kilograms) in 1974 and 616.6 pounds in 1972 compared to 293.7 pounds in 1942, 368.3 pounds in 1952, and 452.7 pounds in 1962.

At the same time that this growth in production and consumption was taking place, the fiber raw material picture has been improving. This is due in part to better management and utilization of our forests, to greatly increased use of mill and forest residues, to broader use of tree species, and to greater efficiency in processing fiber raw materials.

All forecasts indicate a continued future growth of demand and production of paper and paperboard both in the United States and on a world basis. Projections for the United States compared to values for 1972 are shown in Table 2. World demand for paper and paperboard in 2000 is expected to be 456 million tons compared to 155 million tons in 1972. The projected U.S. demand for 2000 is estimated to be 148 million tons or 32 percent of the world consumption.

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Factors Affecting Technological Change

In response to numerous driving forces, the technology of wood processing is undergoing continuous and often drastic change. In order to meet the nation's increasing needs for wood-based materials, future technological advances must occur at a substantially expanded rate.

Future developments leading to more efficient utilization of renewable resources will grow mainly from recent and present trends. Most new processes and technologies take several years after initial research to reach operational stages, so that much of the short-range future can be anticipated.

Included among the numerous factors affecting technological change are construction and equipment costs, energy considerations, legislation and regulations, economic incentives, and, particularly noteworthy, the changing nature of the raw materials base and environmental considerations.

Cost considerations and the availability of capital are most important in the pulp and paper industry which is capital-intensive and each year faces higher capital and operating costs relative to those of other materials industries, including the plastics industry. This implies an increasing cost for these renewable resource products, which tends to restrict the rate at which industry capacity can grow. Cost considerations are, therefore, vital at all stages of pulp and papermaking operations.

Changing Nature of the Raw Material Base

Perhaps the most important factor affecting technological advances in the structural products industry is the rapidly changing nature of the raw materials base. During the period up to the year 2000, most of the accessible, remaining natural forest designated for production will have been harvested and placed under management for sustained and increasingly productive yield. Accompanying this transition will be substantial changes in the size and quality of forest raw materials available for industry. Conversion from old-growth to managed forests will result in a continuing reduction in the size of logs entering manufacture. The long-established trend of more complete utilization of the forest biomass will continue, with the upper limits determined by site and economic considerations. This will further reduce the size, and in many cases the quality, of industrial forest raw material. The ratio of the less desirable hardwoods to the more desirable softwoods available to industry will increase. Hardwoods have provided an increasing proportion of the industry's supply since World War II.

Table 1. Statistics for 1972 characterizing the U.S. pulp, paper, and paperboard industry (excluding hardboard). Tons, where listed, signify short tons; kwh eq, kilowatt-hour equivalent. [Source (4)]

Item	Quantity
Number of establishments	787
Total number of employees	221,100
Total products produced* (tons)	57,491,000
Tons of production per man-hour	0.158
Value added by manufacture (millions)	$ 5,364.2
Total value of shipments (millions)	$11,675.4
Capital expenditures (millions)	$ 891.6
Payroll (millions)	$ 2,455.7
Cost of materials (millions)	$ 5,388.9
Cost of electricity and fuel† (millions)	$ 891.0
Purchased fuel (kwh eq/ton)	5,509
Electric energy purchased (kwh/ton)	470
Generated less sold (kwh/ton)	429
Purchased fuel and electric energy (kwh eq/ton)	5,979
Materials input	
Pulpwood (including harvesting and manufacturing residues) (cords)	71,538,000
Wood pulp (from above pulpwood) (tons)	43,628,000
Waste paper (tons)	11,405,000
Inorganic chemicals, clay, starch, and others (tons)	9,995,000
Nonwood fibers (tons)	1,047,000

*Excluding hardboard (1,909,000 tons). †The figure for contract and resale was $14.9 million.

Forest productivity data indicate that there will be adequate forest biomass, at least until the turn of the century, available to meet the nation's industrial needs. Because of the factors indicated above, technological advances, many of which are now well under way, will be required to utilize this biomass more completely and to adjust to its changing size and quality.

Environmental Concerns

The structural products industries are becoming relatively free from environmental problems because the burning of waste material has nearly ceased except for some small plants. Some problems are encountered by wood preservation plants. Major environmental concerns center around the manufacture of pulp and paper.

Meeting anticipated environmental regulations of the paper industry is expected to be very costly and has resulted in intensive research to mitigate and solve air and water pollution problems. In 1972 the industry spent $339 million in capital expenditures (2) for pollution abatement equipment. Other costs relating to this problem amounted to $243 million. Significant progress has been made by the pulp and paper industry in pollution control, but there is concern over the industry's ability to sustain environmental protection expenditures in excess of the $0.5-billion annual level that has been met during the past 3 years. This includes considerable research expenditures necessary for the development of the best pollution control technology.

Such research expenditures decrease the funds that can be budgeted for other technological developments and for needed capacity expansions. However, the stimulus to solve pollution problems is leading to the development of new technologies for processes that are more environmentally acceptable. These include new pulping and bleaching processes that lead to pollution abatement. Important advances are being made in modifying the kraft process and in the development of new pulping and bleaching processes using oxygen, with concomitant reduction in pollution emissions.

Energy Effectiveness

In view of the high probability of increasing costs of liquid and gaseous fuel, at least until the turn of the century, the relatively low energy requirements for processing wood into primary products, and the degree to which wood processing for many products is self-sufficient are particularly important. As can be expected, energy requirements are related to the extent to which the basic raw material must be altered in processing. In general, the fiber-based industry is understandably more energy-intensive than are many segments of the structural products industry. Essentially all forms of wood processing, however, are superior to the processing of alternative materials from the standpoint of national energy self-sufficiency.

Structural Wood Products

Energy requirements for raw material extraction and its processing to a commodity are shown in Table 3 for selected structural wood products and for commodities used as alternatives. Not only are the gross energy requirements for many wood products substantially lower than alternative products based on nonrenewable materials, but the degree of energy self-sufficiency of many wood products is striking. Softwood and hardwood lumber and hardwood plywood, which in combination account for more than 62 percent of currently used structural wood products, are not only completely energy self-sufficient in the manufacturing process but additionally generate a substantial residue of fuel which can be used elsewhere for industrial or domestic energy. Structural flakeboard, which is not now in production but is highly promising as an alternative to

plywood, will similarly be energy self-sufficient. Softwood plywood, which now accounts for about 13 percent of our structural wood requirements, and laminated veneer lumber, which holds much future promise, both generate adequate processing residue for fuel to supply more than half of the demands for energy required in their manufacture.

More than half of the structural wood products consumed in the United States are used in the construction of residential and light industrial buildings. This expanding market is highly attractive for alternative materials based on nonrenewable resources. A recent study by the Committee on Renewable Resources for Industrial Materials (CORRIM), under the auspices of the National Academy of Sciences/National Research Council, comparing residential construction systems for floors, walls, and roofs incorporating wood and nonwood materials, demonstrated a clear superiority of wood over nonwood alternatives in energy efficiency. Taken into consideration are energy requirements for raw material extraction, processing into building materials, and transportation of materials to the building site. This study shows, for example, that steel floor joists require 50 times as much energy as their wood counterparts performing the same function. Aluminum framing for exterior walls is approximately 20 times as energy-intensive as wood framing. Aluminum and steel studs for interior walls require, respectively, 12 and 8 times the energy of wood studs. Steel rafters exceed wood trusses by a factor of 7 in energy requirement, and aluminum siding requires approximately 5 times the energy of its plywood and fiberboard counterparts. Brick siding requires 25 times the energy of wood-based siding materials. Similar conclusions with respect to commercial structures are drawn from a well-documented study by Bingham (*3*).

The CORRIM study also compared labor and capital depreciation requirements for alternative floor, roof, and wall construction systems and revealed no consistent differences in these requirements for systems based on wood and nonwood components. It appears that, when the conservation of energy is of prime importance, wood is the preferable material for residential and light commercial construction. The insulation characteristics of wood are also superior, which means lower energy requirements for heating.

The Paper Industry

The paper industry is a major consumer of energy (320 billion kilowatt-hour equivalents) which is greater than that consumed by the plastics, rolled aluminum, or plate-glass industries. However, the energy consumed per ton is less than for any of these other materials. Also, the energy cost as a fraction of total manufacturing cost (10 to 16 percent) is less than for such nonrenewable materials as plastics or aluminum.

The paper industry now supplies as much as 42 percent of its energy need from its own process wastes. Therefore, as purchased fuel and power costs increase, the effect on the cost of a ton of paper will be less than the increase in cost of a competing product made from a nonrenewable resource. New technology to improve this capability would further increase this advantage and economize on imported fuel.

Research is under way to reduce energy consumption at the various process steps in the manufacturing operations, such as in refining and drying. Other energy-saving research includes recovering low-level heat from process streams (better heat exchange and recycling), improving generation of energy from processing wastes (better recovery furnace operation), producing low energy, high yield products, reducing the fiber weight in the end-use product, and lowering the brightness requirement for paper.

Efficiency of Material Use

The forest products industry is often considered wasteful of raw material in harvesting and processing. Undeniably, under

Table 2. Statistics and forecasts for paper and paperboard for 1972, 1985, and 2000. Data for hardboard are excluded from the table; figures for hardboard for these years are 1,908,000, 2,885,000, and 4,500,000 short tons, respectively. Figures for the real gross national product (GNP) are $792.5 billion for 1972, $1,222.0 billion for 1985, and $2,000.0 billion for 2000. [Data from the American Paper Institute, New York]

Year	Thousands of short tons				Trend‡
	New supply*	Exports	Imports	Production†	
1972	62,278	2,841	7,626	57,491	78.58
1985	95,155	3,935	10,730	88,360	77.87
2000	148,335	5,710	17,185	136,860	74.17

*Real GNP times trend. New supply = production + imports − exports. Assuming no change in inventories, new supply is considered to be apparent consumption (demand). †Production = new supply + exports − imports. ‡Ratio of new supply to real GNP; extrapolations of past ratios for the future.

Table 3. Energy requirements for selected wood-based commodities and commodities not based on wood. In calculations of supplementary requirements, it is assumed that energy from processing residual fuel can be used only in the manufacturing process and not in extraction. Values in parentheses are for energy from processing residual fuel in excess of that required for manufacture which could be available for other uses. [Source (*5*)]

Commodity	Energy (10^6 Btu/oven-dry ton)				
	Extraction	Manufacture	Total	Available from processing residual fuel	Supplementary requirements for manufacture
Wood-based					
Softwood lumber	0.943	4.846	5.789	8.313	0 (3.467)
Oak flooring	1.073	5.691	6.764	11.388	0 (5.697)
Lumber laminated from veneer	0.740	6.587	7.327	3.540	3.067
Softwood sheathing plywood	0.747	6.871	7.618	3.697	3.174
Structural flakeboard	0.956	7.511	8.467	8.616	0 (1.105)
Medium-density fiberboard	0.783	9.303	10.086	2.741	6.562
Insulation board	0.622	10.539	11.161	0.667	9.872
Hardwood plywood	1.081	10.242	11.283	10.629	0 (0.387)
Underlayment particleboard	4.617	8.101	12.718	1.529	6.572
Wet-formed hardboard	0.743	19.662	20.405	0.797	18.865
Not wood-based					
Gypsum board	0.14	2.73	2.87		
Asphalt shingles	0.03	5.70	5.73		
Concrete	0.52	7.60	8.12		
Concrete block	0.52	7.60	8.12		
Clay brick	0.57	7.73	8.30		
Carpet and pad	6.60	28.69	35.29		
Steel wall studs	2.45	46.20	48.65		
Steel floor joists	2.45	46.20	48.65		
Aluminum siding	26.80	172.00	198.80		

past economic conditions closely related to an abundance of inexpensive large logs of desirable species from wild, old-growth forests, only a small percentage of the resource from the forest entered manufacture. Also, a substantial percentage of the raw material entering the plant became unused residue from the primary product. The changing resource base, accompanied by increasing raw material costs, has stimulated ever-increasing industrial integration with an associated increase in efficiency in the use of all available material. Harvesting technology is being directed to obtain maximum economic removal of as much forest material as can be processed. Processing technology is rapidly being developed to make most species and all sizes of trees and tree parts useful. In the future, the volume of forest residues used can be expected to be influenced by requirements for maintaining site quality rather than by harvesting and processing technology.

The Structural Products Industry

In processing, the quantity of raw material entering the plant for manufacture of the primary product varies with the form and quality of the entering raw material. In today's modern, economically viable plants, the residue from the manufacture of the principal product becomes input raw material for an integrated manufacturing process or fuel to provide energy for manufacture. This reduces or eliminates reliance on fossil fuels. As illustrated in Table 4, absolute waste does not occur in such plants. Less efficient plants, lacking in integration, in which substantial quantities of residue remain unused are still to be found, but their numbers are diminishing.

Better Fiber Utilization

In recent years there has been a continuing trend toward more efficient processing and utilization of wood by the paper industry. For example, there has been a decline in the amount of wood used per unit ton of all pulp types from 1.60 cords per short ton in 1960 to 1.51 cords per ton in 1973. This reduction is partly due to the use of greater percentages of hardwood but primarily it is the result of technological changes enabling the use of higher yield pulps in the manufacture of packaging papers and paperboard, as well as for dissolving pulps.

Since 1950 there has been a shift, not only to a greater use of hardwoods (about 25 percent of all wood pulped), but to integrated utilization of sawmill residues. In 1973 about 38 percent of all wood pulped was in the form of wood manufacturing residues (32.5 percent) and logging residues (5.2 percent), compared to only 17 percent in 1960. When we take into account recycled waste paper and other residual fibers (linters, rags, and bagasse), then more than half the fiber supply that the industry draws upon comes from fibers that would otherwise be discarded. This leads to fuller utilization of the forest resource on an integrated operational basis.

Other waste wood from urban forestry, construction, demolition, pallets, and so forth is another potential fiber source. This is only now beginning to be considered significant.

Today about 22 percent of paper fiber is recycled. In recent years the industry has thoroughly assessed the potential for expanded recycling. It is believed that waste paper recycling will peak at some value less than 30 percent. This figure is based on the economics and technology of collection, handling, and transportation and on the assumption that there will be some degree of public encouragement. This appears to be quite reasonable for the U.S. market and quality demands, since research has shown that the primary fiber has lost its strength potential after about the third recycle. It is possible to regenerate some of its lost potential by chemical treatment, but costs and pollution are factors that mitigate against such efforts.

As more and more of our major cities go to the burning of their organic wastes for heat and energy, the waste paper in this solid waste stream will provide a major combustible component. Only the higher quality and readily collectable clean waste will be recycled for more paper.

Of growing importance is the concept of whole tree utilization, or use of the whole tree above the ground: trunk, branches, twigs, leaves, and bark. Since 1970 there has been some usage of whole tree chips for pulping. As further demands are made on wood and costs rise, there will be greater dependence upon the use of the whole tree. This will fully tap the forest resource and, together with the use of wood manufacturing wastes, will greatly enhance our fiber supply. Moreover, it will lead to better forest management practices to achieve optimum growth rates.

Although wood costs themselves will cause a trend toward wider fiber use and higher pulp yields, developing technologies lend themselves to use of lower quality fiber and higher pulp yields. This is fortunate, and will encourage the development and early application of these new processes.

Table 4. Wood-based primary structural commodities. These materials balance summaries are based on 1 oven-dry ton input of forest-based raw material. [Source (5)]

Principal product	Input raw material	Approximate recovery (oven-dry ton)					
		Principal product	Lumber (studs)	Pulp chips	Fuel	Solubles and volatiles	Other
Wet-formed insulation board*	1/2 bark-free chips, 1/2 forest residual chips	1.04			0.05	0.10	
Underlayment particleboard†	Dry mill residue	0.98			0.11		
Wet-formed primary hardboard‡	1/2 bark-free chips, 1/2 forest residual chips	0.87			0.03	0.10	
Medium-density fiberboard§	1/2 roundwood, 1/2 bark-free chips	0.86			0.17	0.06	
Softwood plywood (unsanded)‖	Roundwood	0.43	0.06	0.30	0.12		0.08 Particleboard furnish
Softwood lumber	Roundwood	0.35		0.29	0.21		0.15 Particleboard furnish
Hardwood plywood (sanded)#	Roundwood	0.30		0.48	0.23		
Hardwood lumber	Roundwood	0.28		0.29	0.23		0.20 Particleboard and medium-density fiberboard furnish

*0.19 ton of starch, wax, and asphalt added to raw materials, mechanical pulping assumed. †0.087 ton of adhesive and wax added. ‡0.02 ton of adhesive and wax added. §0.09 ton of adhesive and wax added. ‖0.01 ton of adhesive added. #0.01 ton of adhesive added.

Legislation and Economic Factors

Legislation and regulations that directly affect the forest industry are those dealing with land use, the environment, food and drugs, energy, occupational safety and health, interstate commerce, consumer protection, building codes, and enhancement of recycling. Environmental regulations have had a large impact upon the paper industry in the past few years and are expected to play a major role in the industry's future.

The amount of capital available for the expansion and improvement of cost effectiveness of a business is limited by the cash flow and profits that can be generated by that business. The extent to which this amount of capital is allocated to facilities or operations that are solely designed to meet governmental regulations, such as those pertaining to the environment, without increased production or product improvement, reduces the amount available for capacity expansion, cost reduction, and product improvement. Furthermore, older plants may have to be closed prematurely because they cannot afford to meet new environmental requirements, causing local unemployment. Consequently, productive capacity could be curtailed and fall behind product demand. This and the failure to reduce costs lead to higher prices and inflation.

Economic incentives may take the form of outright grants, investment tax credits, or other special legislation available to the government to encourage the adoption of new technology and concepts to expand and improve the utilization of the renewable wood material resource. If other factors do not interfere, economic incentives can speed up acceptance of new technology and operating concepts by as much as 5 years.

Recommendations

The forest products industries as a whole have needs which apply to all its segments. In addition, the major components of these industries have their own special needs. The recommendations to fulfill these needs are listed accordingly.

The Forest Products Industries

1) Centers of excellence for the education of scientific manpower in wood and fiber science and technology should be maintained with governmental support at leading universities.

2) Substantially increased research directed toward advancing technology in wood and wood-fiber materials must be strongly encouraged with governmental financial support where needed.

3) Because of the decreasing size of available timber and the increasing necessity to utilize a higher percentage of the forest biomass, it is important to develop cost-effective methods of recovering forest residues and other material of small and irregular size.

4) Attention must be directed to reducing power consumption in all phases of logging, manufacture, and transport in the forest products industries.

5) There should be economic incentives to maintain the growth of the forest-based industries and enable them to invest in innovative activities by (i) outright grants, (ii) investment tax credits, (iii) financial assistance for capital costs, for research in environmental control and energy efficiency, and for research and development activity in engineering, production and marketing of new products and processes, and (iv) legislation to encourage the adoption of the technology and concepts to expand and improve the utilization of the renewable wood resource and the protection of the environment.

The Structural Products Industry

1) Inasmuch as the future structural products mix must consist of ever-increasing percentages of reconstituted products, concentrated research must be directed toward improving processes of manufacturing structural materials suitable for exterior and interior use from hardwood and softwood flakes, strands, veneer, fiber, and pieces of small size, alone or in combination. An associated need is the development of inexpensive adhesives, not petroleum-based, for reconstituted products, with particular attention to an exterior adhesive which can serve the function of the currently used phenol-formaldehyde. Lignin from wood could be a potential source for the development of such adhesives.

2) Because a major portion of the energy required for the manufacture of wood structural materials can be provided from processing residue, research should be directed to the development of economical greenwood and bark burners for direct-fired dryers and wood-fired boilers. There should also be research on the development of dryers, heating coils, and hot-presses of high thermal efficiency.

The Pulp, Paper, and Paperboard Industry

1) The renewable wood fiber industries should be encouraged to reduce further the consumption of energy and thereby not only help improve the overall energy situation, but also reduce costs and improve competition with nonrenewable materials. This can be done by (i) reducing energy used in processing by heat exchangers, thermal recycling, and closed loop systems, (ii) improving generation of energy from processing wastes, and (iii) producing lower energy, high yield products.

2) There should be a concentrated research effort by the industry with governmental support. Present funding for research in the pulp and paper area is about $250 million annually, of which about 40 percent goes for maintaining present equipment and technology and the remainder for innovative research. This expenditure is about 0.6 percent of the industry's sales value or about 9 percent of its capital outlays, which is small compared with budgets dealing with other materials and processes. The crises in energy and scarce materials call for immediate steps to permit the renewable fiber industries to improve their products, reduce energy, improve their competitive position with respect to petrochemical and other nonrenewable materials, and improve processing efficiency by increasing yields, reducing wastes, lowering costs, and enhancing the quality of the environment. To achieve most of these goals for the paper industry by 1985 requires that the innovative component of the overall research effort be increased to a figure of around $450 million now and then be kept level with inflation. This figure plus the continued maintenance research cost of $100 million (in 1975 dollars) would bring the total annual research expenditure to about 1.3 percent of the present sales value. These figures are for R & D only. Commercial implementation will require continued large capital investments to meet environmental, energy, and innovative process and product demands over the next decade.

3) Governmental regulations, especially those pertaining to the environment, should be implemented and administered in such a way that (i) their impact upon the consumer and the renewable fiber resource industries is reasonable and (ii) the health of these renewable industries is not endangered, but instead maintained in sound condition.

References and Notes

1. In the United States, 98 percent of the fiber for paper and paperboard is derived from wood.
2. Data from the National Council of the Paper Industry for Air and Stream Improvement, Inc., New York.
3. C. W. Bingham, *For. Prod. J.* **25** (No. 9), 9 (1975).
4. Data from 1972 Census of Manufactures, Washington, D.C., and the American Paper Institute, New York.
5. Data from "Renewable resources for structural and architectural purposes," report of Panel II, Structural Purposes, Committee on Renewable Resources for Industrial Materials, National Academy of Sciences/National Research Council.
6. We thank the National Academy of Sciences/National Research Council for permission to draw upon material gathered by the agency's Committee on Renewable Resources for Industrial Materials (CORRIM). We thank the members of the CORRIM panel on structural purposes (S.B.P., chairman), Conor Boyd, Peter Koch, Herbert McKean, C. R. Mortschauser, and Fred Wangaard, and the members of the CORRIM panel on fibers (F.C.J., chairman) dealing with paper and paperboard products: Richard Auchter, A. Stanley Gregory, Alfred Nissan, and Ronald J. Sloss.

The National Forests

A great national asset is poorly managed and unproductive.

Marion Clawson

The national forests of the United States are a great national asset, include 8 percent of the national land area, have a value estimated at $42 billion, and in recent years have produced cash revenues of $400 million to $500 million annually. Their output and use affect everyone in the United States, directly or indirectly (*1*).

The national forests are owned by the people of the United States and are managed by the federal government, more explicitly, by the Forest Service. The forests are managed on multiple use principles, with due regard for outputs of timber, outdoor recreation, wilderness, wildlife, and water (*2*). They are used by private individuals and companies. Other extensive forests are owned by the federal government but managed by other agencies. Still other forests are owned by state and local governments, by forest industry firms, or by a class usually labeled "other" because it includes a great variety of owners. The national forests include 18 percent of the commercial forest land of the country but now include slightly more than half of the standing softwood timber, and a smaller proportion of the hardwood timber (*3*).

The national forests are located largely in the West because they were established by the reservation of public domain for permanent public ownership. By 1891 when such reservations began, most of the suitable public domain was in the West (*4*). However, under legislation passed in 1911, considerable acreage was purchased from private landowners, primarily in the South, the Northern Lake States, and the East. Half of the area of the national forests are classed as commercial forests; the rest is above timberline, or is covered with shrubs and grasses, or has forests too sparse to be considered "commercial." The commercial stands of the national forests are primarily softwood species and much of the timber is old growth, or "virgin" (*5*). The old stands typically show little net growth annually and cannot be made to grow much more wood until the old timber has been harvested and replaced by new, more economical, faster-growing stands. Some of the most difficult problems of forest management involve this conversion of old growth to younger stands. There exists a good deal of popular confusion about the use of virgin timber stands. While the cutting of timber cannot indefinitely exceed annual growth because timber inventory would eventually be exhausted, neither can growth indefinitely exceed cutting because fully mature, uncut stands show little or no growth. Any cutting of old growth means cutting more timber than is growing until the annual net growth on the previously cut areas equals the volume cut annually from the old growth stands.

National forests, like all other forests, differ substantially in site productivity, often within rather short distances (*1, 6*). The average per acre growth potential of the national forests (for fully stocked natural stands not subject to intensive management) is slightly below the average for all forests and considerably below the average of forest industry forests. However, these differences are much less if the Site Class V lands, which are of dubious value in their timber growing potentialities, are omitted. The actual amount of timber growth on national forest land is low, both in volume of wood per acre annually and in relation to potential growth, primarily because the virgin stands are growing slowly or not at all (Table 1). In 1970, actual net growth of wood on national forest lands was only 39 percent of potential growth for fully stocked but not intensively managed natural stands, while in the forest industry forests net growth was 59 percent of the potential (*6*).

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Past Trends in National Forest Use

Over the past 40 years, the use of every kind of forest output from the national forests increased by varying but substantial amounts (Table 2) (*7-9*). This comparison omits grazing on national forest land, much of which occurs on noncommercial forest areas, and mineral production. Since the use of each output of commercial forest lands increased, the sum usage of all outputs also increased. This conclusion is possible without calculating an index of combined output. Although each of the various uses of the national forests may, and sometimes does, impinge adversely on other uses at particular times and places, all uses have increased in the long run.

The increased harvest of timber from national forests was accompanied by major increases in the price of "stumpage" or standing trees. Whereas the annual average price of all timber sales from national forests varied only between $2 and $3 per 1000 board feet from 1924 to 1942, by 1972 the average price had risen to nearly $40, while prime logs in good locations were two to five times higher in price. This rise in average prices understates the extent of the increase in price for logs of the same quality in comparable locations, because the recent price includes logs of a quality or location (or both) which would have been valueless at one time. The other outputs of the national forests are free or negligible in price.

Potential Output from National Forests

The output of every kind of good and service from national forests could be increased (Table 3). In considering potential, at least two questions arise: (i) whether the potential is purely biological or whether it is also economic; and (ii) whether the potential for each kind of output should be considered separately, without regard for competing outputs, or whether all outputs should be considered at the same time. Table 3 shows a combination of the extremes of these considerations; that is, biological output of each good and service managed for its maximum output with other outputs in a subordinate but often significant role; and an economically defensible output with the use of each kind of good or service adjusted to the demands for the other services. While these estimates are approximate, they demonstrate the potential for substantially increased output of each major kind of good or service.

The second type of potential output

(economic) in Table 3 could be achieved only by the application of new technology and usually only by greater investment of capital or greater expenditures for current operation or both. For wood, this would include (i) prompt planting with improved species in order to achieve a good new stand within a year instead of a hit-or-miss stand from natural reseeding in an average period of 7 years; (ii) planting at the optimum spacing to take full advantage of the sun, water, and fertility of the site; (iii) periodic thinnings as the stand grew in order to harvest and use wood which would otherwise rot in the forest; (iv) fertilization at appropriate times; and (v) complete harvest when the trees reach economic maturity. For other outputs, roughly similar intensification measures would be needed. Even wilderness areas could be managed intensively to provide more trails at appropriate locations, to space out visitor parties to avoid conflicts, and to otherwise allow more users in a given wilderness area without loss of quality in the wilderness experience.

In the 1920's there was much unused potential output from the national forests. While this fact was realized at the time by Forest Service managers, the extent of that unused potential is more readily apparent now than it was then. Given today's technology, there still exists much unused potential output from the national forests. The unused potential now is not as great in percentage terms as it was in the 1920's, but is greater in absolute amounts. Forty years from now our descendants may have achieved increased output in ways that are not now apparent. The best trade-offs between one kind of output and another and the optimum intensity of production are complex and detailed questions beyond the scope of this article.

Economics of National Forest Management

The national forests are big business in the modern American sense of that term. Had they been an industrial enterprise, their cash income alone would have ranked them about halfway up on *Fortune*'s list of the 500 largest industrial firms in the United States during each of the past 20 years or more, and their total income and total assets would have ranked them still higher. Yet they have never been studied and analyzed as business enterprises, a failure which has serious consequences for their management for social purposes.

The national forests, as public enterprises, are not managed for profit in the way private business is. However, costs, output, and efficiency are no less important for public than for private enterprises. Economizing in the use of scarce resources and productive factors to produce desired outputs (whether sold for cash or not) is as applicable to public as to private enterprises. Wilderness, recreation, wildlife, water, and some other outputs of national forests are available to the public free or at prices substantially below their economic value, but this is also true for the same outputs of privately owned forests. The problem of securing a direct financial return comparable with the economic value of these outputs is a persistent and nearly ubiquitous one in forestry.

Table 1. Growth of sawtimber in board feet per acre of commercial forest, national forests and timber industry forests, 1970 (*1*).

Growth	National forests	Forest industry forests
Gross	176	220
Mortality loss	68	35
Net	107	185

A financial balance sheet can be constructed for the national forests (Table 4). This is a simplified version of a typical business balance sheet, constructed from the best data available (but data which were never intended for this purpose). Several aspects of this balance sheet are worthy of particular attention. First, cash receipts are less than half of the total income. Second, cash receipts nearly equal cash expenditures. Third, capital charges that are reasonable in comparison with the immense value of the national forests dominate the cost side of the balance sheet. If the facts are interpreted on this basis, the national forests incurred a deficit of nearly $2 billion in total or about $9 per capita of the whole population. Since the deficit is a bookkeeping one, another and perhaps more reasonable way of describing the overall result is to say that national forests earned less than 0.5 percent on their investment, even when all noncash outputs are valued generously.

The regional pattern of national forest expenditures is economically unsound. During the 5 years 1970–74 there was only a limited relation between cash expenditures for management purposes and cash receipts, by national forest regions (Fig. 1). It seems to cost $20 million to $30 million to manage a national forest region even when cash receipts are very low, and expenditures do not rise in proportion to revenues. The situation is more extreme for cash investment expenditures (Fig. 2). There is very little relation between the amount of cash receipts and the amount of cash investments.

If all outputs and costs, including capital charges, were calculated at their full mar-

Table 2. Average annual harvest of timber and wildlife and use of recreational opportunity, and water from national forests, 1925–29 and 1968–72.

Item	Annual average		1968–72 as multiple of 1925–29
	1925–29*	1968–72†	
Timber cut	1.35‡	11.54‡	8.6
Wildlife	216§	582§	2.7
Recreation visits	6.3‖	188¶	30
Water#			Probably 2.0

*Data from (*8*). †Data from (*9*). ‡Amount given in billions of board feet. §Thousand big game killed by hunters. ‖Million recreation visits. ¶Million visitor days, 1973. #No data are available on use of water flowing off national forests. With the volume of public and private dam building, use in the latter period can hardly be less than double the former, even if total streamflow is unchanged.

Table 3. Current and potential outputs of national forests. Potential output is given on a biological basis with each use considered dominant, other uses subordinate, and no concern for economic efficiency, and on an economic basis with each use adjusted to other uses.

Kind of output	Present output*	Potential output†	
		Biological basis	Economic basis
Wood grown annually (billion cubic feet)	2.6	10.5	6 to 7
Wilderness area‡ (million acres)	11.6	55	40
Outdoor recreation (million visitor days)	188	1000	400
Water yield (volume)	Not measured	25 percent more	10 percent more
Wildlife, all kinds	Not measured	Many more	Slightly more

*1970 for wood, some more recent year or average of years for others. †My estimates, see text for basis. ‡Formally designated wilderness areas, excluding de facto wilderness. Assumes no major relaxation in definition of wilderness with regard to size of tracts or degree of nonwilderness use tolerated. Acreage is, at best, a measure of the opportunity for wilderness use and not a measure of output.

ket value, the old test of marginal value equaling marginal cost would be applicable in the management of national forests, whose great size makes them a major factor in all markets for their outputs. In the absence of the necessary data for such a comprehensive analysis, a comparison of cash receipts and cash expenditures by regions may serve as a reasonable indicator of the relation between value and cost.

The unsound regional pattern of national forest expenditures extends to timber management (Fig. 3). Expenditures for timber management, reforestation, and timber stand improvement are higher per 1000 board feet in regions where values per 1000 board feet of the timber sold are low than where they are high. The situation was more marked in 1972 when stumpage values were comparatively low than in 1973 when the sale price of stumpage was high. In some regions costs equal or exceed values of timber sold. These costs do not include general administrative costs, fire fighting, insect and disease control, and some other national forest expenditures, some parts of which are properly chargeable to timber management. If these other costs could have been included in the analysis, the picture would have been worse.

A comparison of cash expenditures for all purposes with all cash receipts by individual national forests reveals a similar lack of rationale (Fig. 4). It seems to cost $1 million to $3.5 million to manage a national forest, regardless of the amount of cash receipts, whereas relatively little more is spent in the management of those national forests with large cash receipts. An analysis of typical forests in the Southwest, where timber values are comparatively low, shows that as much or more is spent per acre as in the Pacific Northwest where timber values are very high.

A complete accounting of the economic value of all national forest outputs, including those provided essentially without charge to their users, would change the income situation of all regions and forests. However, a complete accounting of all costs, including reasonable capital charges for the large amounts of capital tied up in the national forests, would also change our view of the cost situation of all regions and forests. It is by no means clear that the relative relation of costs and income would be changed thereby. The regions with high timber values, such as California, are also regions of high watershed, recreation, and wilderness values.

The data in Figs. 1–4 do not relate explicitly to expenditures by productivity classifications of sites in the national forests. Given the difficulty of allocating expenditures by specific locations, such data would be hard to obtain in any case. However, all the indications are that too much money is spent in management of low productivity sites and too little on high productivity sites. The pattern of expenditures by regions and by forests and the general disregard of economic considerations that underlie this pattern strongly suggest that allocations by productivity site class are also uneconomic. These statements about site class apply equally well whether one considers only timber production or whether one also considers wilderness, recreation, wildlife, and water, although the site specifications would differ for each.

The national forests are wasteful in their use of capital. Forestry always involves heavy use of capital, for land, for standing timber, for roads and other improvements, and for other purposes. The capital in standing timber is peculiar in the sense that the same tree is called capital if allowed to stand for further production but is called output when cut. If the national forests are judged by the standard of forest industry forests or by the standards of economically optimum rotations for which Forest Service research has provided the necessary basic data, there is at present $12 billion in excess timber inventory on national forests (*10*). The mature forests, where net growth is low, sometimes even negative, and where rot takes a large annual toll, are examples of extremely large amounts of nearly idle capital. At modest interest rates, a $12 billion excess inventory in standing timber means an annual cost of $600 million in total or about $3 per capita of population. One can readily imagine the reaction if every citizen of the United States was asked to contribute $3 annually toward the maintenance of an excess inventory of old trees

Table 4. Financial statement for national forests, circa 1974.

Account item	Total national forest system (million $)	Per acre of	
		Entire acreage ($)	Commercial forest acreage
			Classes I–V ($)	Classes I–IV ($)
Capital structure:				
Value of standing timber*	20,000	107	217	324
Value of forest land†	20,000	107	217	324
Undepreciated value of man-made improvements‡	2,000	11	22	32
Total assets	42,000	225	456	680
Cash investment§	196	1.05	2.13	3.08
Investment in kind‖	120	0.64	1.30	1.94
Value of increased timber inventory, 1970 volume, 1974 prices¶	42	0.22	0.46	0.68
Income:				
In cash#	486	2.60	5.28	7.88
In kind**	220	1.18	2.39	3.56
Additional value of products and services provided at less than full market prices††	490	2.62	5.32	7.93
Total annual output‡‡	1,238	6.63	13.45	20.05
Expenditures:				
In cash, all purposes	488	2.62	5.31	7.91
In kind§§	220	1.18	2.39	3.56
Depreciation of man-made assets, 10 percent	200	1.07	2.17	3.24
Payments to states and counties	79	0.42	0.86	1.28
Interest on all assets, 5 percent	2,100	11.23	22.80	34.00
Total	3,087	16.51	33.53	49.99
Net annual income, cash and noncash	(1,849)	(9.87)	(20.08)	(29.94)

*A 1970 inventory of 1021 billion board feet of sawtimber on national forests is given in (*1*). On the basis of $40 per 1000 board feet, which is an approximate recent average for timber sold from national forests, the value of the standing sawtimber (ignoring values for growing stock of less than sawtimber size) would be slightly in excess of $40 billion. This value has been cut in half to reflect a reasonably early (10 to 20 year) liquidation value. †Excludes timber values; averages about $110 per acre for all national forest land; also assumes reasonably early liquidation value. ‡Clawson (*8*, p. 54) reports $1160 million in 1963; estimated to have risen to $2000 million by 1974. §Data from Forest Service; roads, trails, other construction, and purchase of land (*14*). ‖Road building allowance in timber sales contracts; 12 billion board feet, assumed $10 per 1000 board feet road building allowance in sale price. ¶In 1970 harvest slightly exceeded growth for softwood growing stock but growth exceeded harvest by about 450 million cubic feet for hardwood growing stock (*1*). Converted to board feet, this is 6 board feet per cubic foot, $80 per 1000 board feet for softwood, $30 per 1000 board feet for hardwood. #Includes receipts from mineral leases on national forest lands acquired by purchase from private owners; excludes them from national forest lands reserved from public domain. **All of road building allowance plus $100 million in working funds, cooperative agreements, and the like where the national forest user agrees or is required as a condition of timber harvest or other use to undertake certain restoration or other activities. ††Estimated on basis of 170 million recreation visits other than wilderness at an average value of $2 each, 10 million wilderness area visits at an average value of $10 each, and water supply at $50 million. Wildlife values assumed included in recreation and wilderness values. States may benefit from wildlife values, for instance in sale of hunting licenses. No allowance is made for the possibility that wood and forage are sold at less than a full value. ‡‡Increased timber inventory, cash and kind receipts, and values of products not sold for cash. §§These are the same items described in **; they appear both as income and as outlay.

that he might never see. This calculation of excess timber inventory has nothing to do with wilderness areas; even if they were to be reserved generously the excess timber issue would still remain.

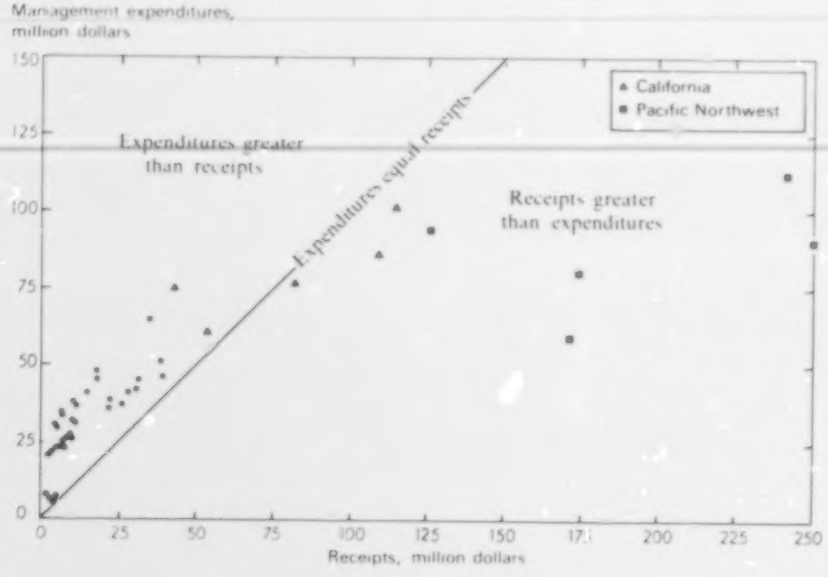
The data strongly suggest that the national forests are functionally inefficient also. In particular, expenditures for timber management are being made in regions, on forests, and on sites where timber values are so low that the areas should be abandoned for timber growing purposes. Other outputs of these forests may be worth managing, and existing stands of trees may be valuable for this purpose, but the growing of more timber is not economically sound.

Some forest practices are almost surely economically inefficient also. Substantial sums are spent in timber surveys, appraisals, and sales (*11*). The stumpage (standing trees) is sold to private buyers. Although there is sometimes active competition for the stumpage, sometimes there is not, and to prevent the stumpage from being bid in at unreasonably low prices, the Forest Service makes elaborate timber appraisals. Where there is active competition, the bid prices often greatly exceed the appraisals since a processor may be better off to pay more than the timber is worth than to risk having his mill inoperative for lack of logs. If standing timber were cut by independent contractors or employees paid by the Forest Service and the logs transported to a central log yard, graded, and auctioned off, more money could be realized from the logs and substantial savings in management costs could be achieved. Other Forest Service practices might also be questioned on grounds of economic efficiency — for example, it may not be economical to fight fires or to control insects everywhere they appear.

A careful analysis of the best available data on timber management expenditures by large forest industry firms suggests that the Forest Service has available for expenditure on timber management somewhat less money (perhaps a fourth less) per acre of commercial forest than these private firms spend (*12*). The overall amount of expenditures for timber management in national forests is not too high and may well be too low; the geographic distribution and functional and practical allocation is uneconomic. Unfortunately, similar comparisons for outputs of the national forests other than wood cannot be made on the basis of the available data.

In any economic evaluation of national forest management, the free or nearly free services of wilderness, recreation, wildlife, and water are mischief-makers. Their price, arbitrarily established at well below market value, encourages wasteful use in the following ways: (i) services priced as if they are free are treated as if they are valueless; (ii) the Forest Service and the various other decision-makers in the federal budgeting and appropriation process lack clear guides to rational amounts of expenditures; and (iii) some parties gain substantially while others gain not at all or lose — an income redistribution that is not explicit but nevertheless may be considerable. The use of the best available shadow prices would solve the second of these problems.

The capital used by the Forest Service is available without specific interest or other charge. The value of the timber and land in the national forests is very large and any reasonable interest rate results in an annual charge that dominates the whole cost side of the national forest business sheet. Yet no charge is made for this capital — in fact, only rarely is its existence acknowledged. The Forest Service operates as if this capital were free. Even the capital invested in roads, reforestation, and other improvements does not bear a specific annual charge. The Forest Service may have great difficulty getting appropriations for such investments, but the difficulty is political and not in economic accounting. Capital which seems to be free is an irresistible temptation to its wasteful use.



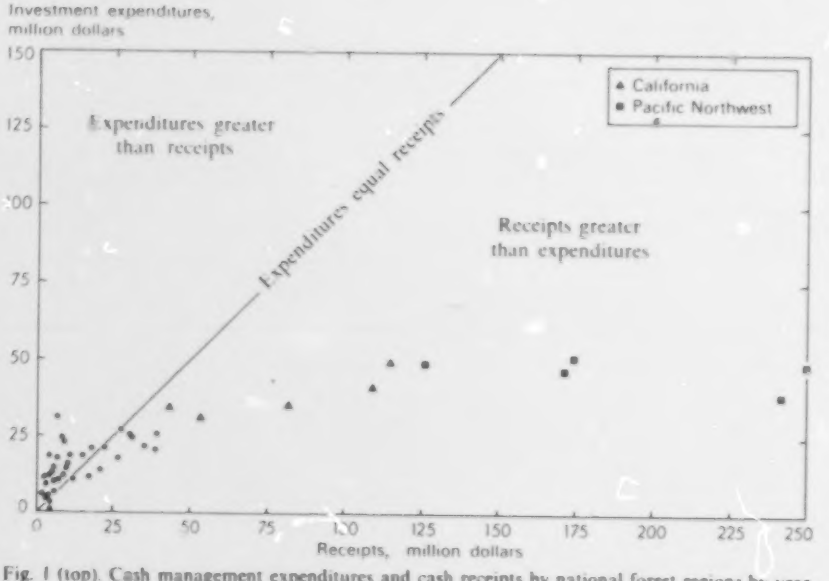


Fig. 1 (top). Cash management expenditures and cash receipts by national forest regions by year, fiscal 1970 to fiscal 1974. Fig. 2 (bottom). Cash investment expenditures and cash receipts by national forest regions by year, fiscal 1970 to fiscal 1974.

Why Are the National Forests So Economically Unproductive?

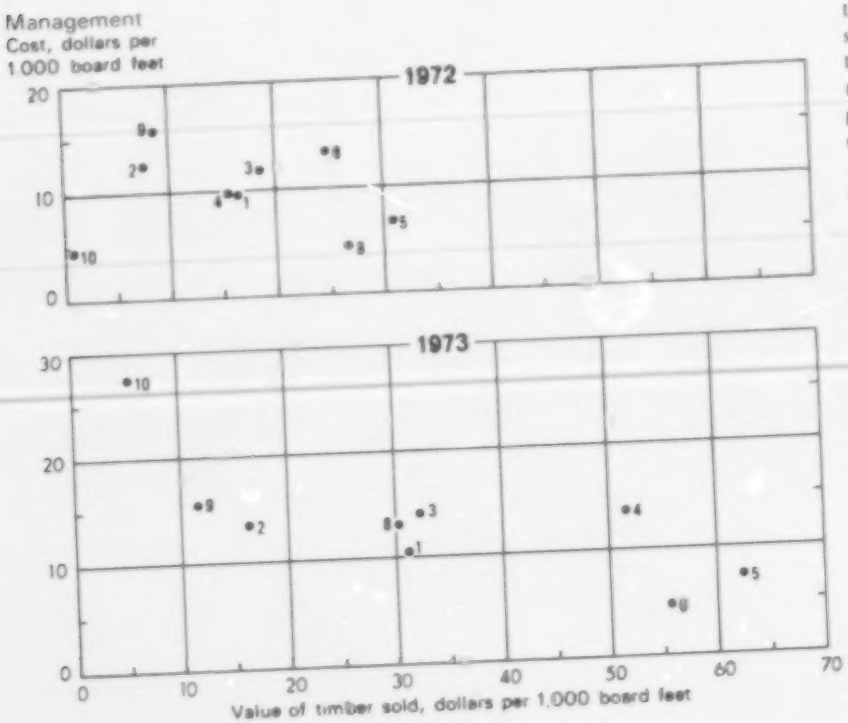
A number of factors, forces, and organizations are responsible for the economically unproductive management of the national forests. Each factor, force, or organization taken alone would be serious; their combination is, to an economist, disastrous.

Responsibility for the management of the national forests is seriously dispersed in the federal government. The Forest Service, the Secretary of Agriculture, the Office of Management and Budget, and the Congress each have a major role, and other units have lesser but sometimes significant roles. Each offers direct constraints on the others, and each may indirectly influence the perceptions of others with regard to the positions of various actors in the process. It is virtually impossible for an outsider to fix responsibility; one suspects that the actors are not always clear as to why decisions are made or not made. In particular, there has been a lack of a clear policy directive for the Forest Service in its on-the-ground management of the national forests. The Multiple Use Sustained Yield Act of 1960 is vague in its directive, and its very vagueness may have been one reason it was acceptable to the various interest groups.

The free outputs from the national forests, such as wilderness, wildlife, and water, make rational economic planning very difficult. The free capital embodied in the national forests similarly distorts economic management. There has been a notable lack of economic tests for forest practices and management at all levels, from the specific site in the forest, to the ranger district, to the national forest, to the Forest Service region, to the national level. None of the actors in the management process, from forest ranger to President and congressman, have insisted on the careful weighing of costs and benefits which is the essence of economic management.

In any accountability for the results of national forest management, the attitude of professional foresters, or at least those in the public employ, must bear a substantial share of the result. Many foresters have ignored economics, and some have been strongly anteeconomic in their philosophy. They have emphasized ecological considerations, multiple use, sustained yield, even flow, community stability, and other concepts which may have had meaning to them, and often were strongly, even emotionally held, yet had little precise meaning to others or in practice. An attitude that costs, benefits, and other economic considerations did not apply to public forests has somehow been common. In practice, multiple use has all too often meant a little of everything everywhere, including timber management on uneconomic sites.

The general public, the conservation organizations, and the information media must also accept some responsibility. Often the focus has been on some relatively small issue, such as a particular clear-cut or a particular potential wilderness area, while at the same time the possibilities of each interest group obtaining most or all of what it seeks by more intensive and skillful national forest management has gone unnoticed or unremarked.



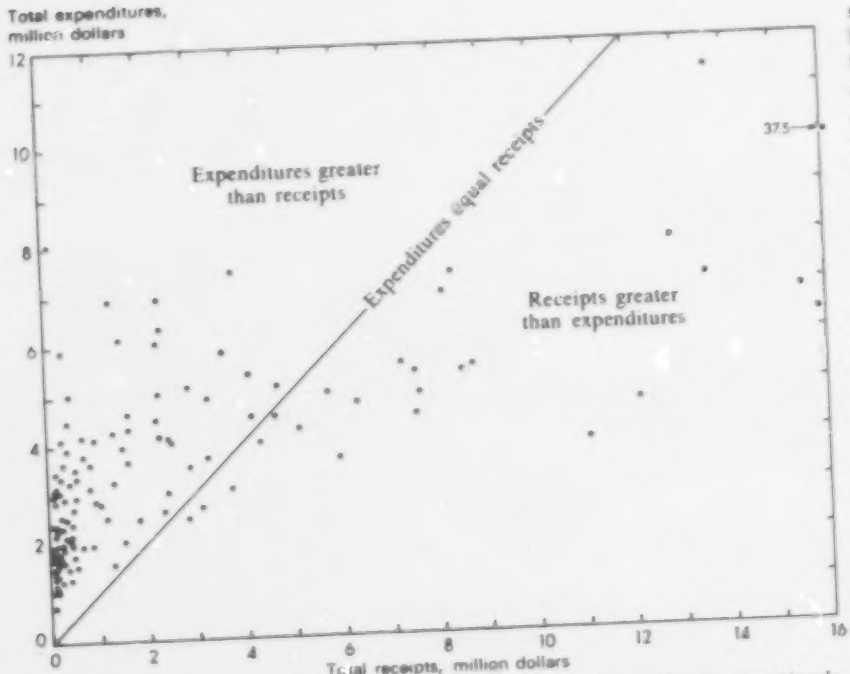


Fig. 3. (top). Cash-cost of timber management, reforestation, and timber stand improvement in relation to value of timber sold, for nine national forest regions, 1972 and 1973. Fig. 4 (bottom). Total cash expenditures and total cash receipts by national forests, fiscal year 1972.

What to Do?

Several steps are necessary if there is to be a national commitment to make the national forests best serve the needs of all the American people. An uneconomic use of capital, an output of national forests significantly below their economic potential, management costs and practices that are not efficient, and other aspects of national forest management described in this article do not serve the American people well. Three major kinds of actions are necessary.

1) There must be an alert, intelligent, and continuous national leadership for good national forest management. In particular, a concerned President, some sympathetic but tough-minded senior staff at the Office of Management and Budget who will remain on the same job for several years, a secretariat in Agriculture that is responsive to national forest possibilities and willing to devote some energy to them, and a Congress which continuously demands answers to the pressing questions about costs and benefits and then backs up its decisions with adequate funds are all essential.

2) There must be new procedures and new analyses to test economic rationality, from small timber sale area to national decisions on expenditure and investment. There are problems in doing this without creating bureaucratic and procedural monstrosities that would defeat the purpose. Nonetheless, past and present methods of management, especially the economics thereof, are no more sacrosanct than are past methods of cutting trees with axes and saws and dragging logs from the woods with the use of horses. Imaginative innovation can surely create means to deal with the problems if there is a will to do so.

3) There must be a massive infusion of new blood into the Forest Service—at least a third of the national forest management staff should be recruited from sources outside the Forest Service. Promotion within the service has many virtues, but in the end the closed society it creates is unable to cope with new problems (*13*). Without enough new people to significantly modify the nature of the Forest Service, progress will be slow, halting, and uncertain. The need today is not for forestry expertise; the Forest Service has that, or knows where it can get it. The need is for new economic and social vision.

Summary

National forests are a valuable national asset. They produce important amounts of wood, recreation, wilderness, wildlife, and water, but good management could produce much more of each kind of output. The national forests are a major business enterprise, with $42 billion of assets and an annual cash revenue of $400 million to $500 million, but they have never been studied as business enterprises. The national forests are capital-intensive, but the capital is used wastefully, in large part because no charge is made for its use. Funds for management and investment are spent in economically unrewarding regions, forests, and sites. The availability of so much of their output at little or no cost to users seriously distorts management decisions. Major reforms in the management of the national forests are needed. If carried out, these could make the national forests much more useful to the American public.

References and Notes

1. The source of much of the basic data for this article is *The Outlook for Timber in the United States* (Forest Resource Report No. 20, Forest Service, Department of Agriculture, Washington, D.C., October 1973). This source and many others give relatively detailed data for 1970, hence this is used as the usual base year. Where significant changes have occurred in more recent years or where data for a single year might be misleading, trend data or averages for periods of years are used. The financial data in the latter part of the article refer to various years after 1970; the choice of year depends in part on economic conditions that year and in part on data availability. Consistent use of a single recent year would be highly desirable but is not possible. I hope that using different years does not confuse the reader since the analysis is improved by use of the years chosen.

   It is unfortunate that such anachronistic terms and concepts as "sawtimber" and "board feet" have not been replaced in practice by "wood" and "cunits" (100 cubic feet), respectively, for these are far more relevant to modern forestry. To permit easier comparison with earlier and current writings about forests, I have retained the outmoded terms and concepts in spite of my distaste for them.
2. Books that present an overall view of the national forests and the Forest Service are: D. Barney, *The Last Stand* (Grossman, New York, 1974); M. Frome, *The Forest Service* (Praeger, New York, 1971); G. O. Robinson, *The Forest Service: A Study in Public Land Management* (Johns Hopkins Press, Baltimore, 1975).
3. Basic to all discussions about forests in general and about national forests in particular are two definitions taken from (*1*):

   Forest land: "Land at least 10 percent occupied by forest trees of any size, or formerly having such tree cover, and not currently developed for nonforest use. The minimum area for classification of forest land is 1 acre. Roadside, streamside, and shelterbelt strips of timber must have a crown width at least 120 feet wide to qualify as forest land. Unimproved roads and trails, streams, or other bodies of water or clearings in forest areas are classed as forests if less than 120 feet in width."

   Commercial timberland: "Forest land producing or capable of producing crops of industrial wood and not withdrawn from timber utilization. Areas qualifying as commercial timberland have the capability of producing in excess of 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included, except when the areas involved are small and unlikely to become suitable for production of industrial wood in the foreseeable future."
4. J. Cameron, *The Development of Governmental Forest Control in the United States* (Johns Hopkins Press, Baltimore, 1929); S. T. Dana, *Forest and Range Policy: Its Development in the United States* (McGraw-Hill, New York, 1956); P. Gates, *History of Public Land Law Development* (Government Printing Office, Washington, D.C., 1968); W. B. Greeley, *Forests and Men* (Doubleday, Garden City, N.Y., 1951); B. H. Hibbard, *History of Public Land Policies* (Macmillan, New York, 1924); J. Ise, *The United States Forest Policy* (Yale Univ. Press, New Haven, Conn., 1920); E. L. Peffer, *The Closing of the Public Domain* (Stanford Univ. Press, Stanford, Calif., 1951); G. Pinchot, *Breaking New Ground* (Harcourt, Brace, New York, 1947); R. M. Robbins, *Our Landed Heritage* (Princeton Univ. Press, Princeton, N.J., 1942); H. Steen, unpublished history of the Forest Service.
5. The following publications about forests in general and national forests are relevant to my discussion: W. A. Duerr, Ed., *Timber!* (Iowa State Univ. Press, Ames, 1973); G. R. Gregory, *Forest Resource Economics* (Ronald, New York, 1972); D. M. Smith, *The Practice of Silviculture* (Wiley, New York, 1962); S. Spurr and B. Barnes, *Forest Ecology* (Ronald, New York, 1973); A. Worrell, *Principles of Forest Policy* (McGraw-Hill, New York, 1970).
6. *Report of the President's Advisory Panel on Timber and the Environment* (Government Printing Office, Washington, D.C., 1973), p. 35; M. Clawson, Ed., *Forest Policy for the Future: Conflict, Compromise, Consensus* (Resources for the Future, Washington, D.C., 1974).
7. M. Clawson and B. Held, *The Federal Lands: Their Use and Management* (Johns Hopkins Press for Resources for the Future, Baltimore, 1957).
8. M. Clawson, *The Federal Lands Since 1956: Recent Trends in Use and Management* (Resources for the Future, Washington, D.C., 1967).
9. *Agricultural Statistics 1974* (Government Printing Office, Washington, D.C., 1974).
10. M. Clawson, *Forests For Whom and For What?* (Johns Hopkins Press for Resources for the Future, Baltimore, 1975).
11. W. J. Mead, *Competition and Oligopsony in the Douglas-Fir Lumber Industry* (Univ. of California Press, Los Angeles, 1966).
12. M. Clawson, in preparation.
13. H. Kaufman, *The Forest Ranger: A Study in Administrative Behavior* (Johns Hopkins Press, Baltimore, 1960).
14. J. R. McGuire, personal communication, disclosures, 17 July 1975.
15. This article draws heavily on (*12*), as well as on (*10*), and (*6*) which I wrote or to which I was a major contributor. My debt to many persons is acknowledged in those sources and need not be repeated here. I am particularly indebted to William F. Hyde of Resources for the Future and to Lawrence W. Libby of Michigan State University for their active involvement in my research and for my use of some of their unpublished facts and ideas.

Agricultural Residues and Other Nonwood Plant Fibers

Potentially important renewable resources in the developing world are discussed.

Joseph E. Atchison

Many of the developing nations of the world, as well as some of the highly industrialized countries, do not have adequate supplies of wood nor the available land for increasing their wood supplies. However, many of these same countries do have large quantities of fibrous agricultural residues and other nonwood plant fibers which represent another renewable source. Many of these fibers can be used for the same purposes as wood, especially for manufacture of pulps, paper, paperboard, and reconstituted panelboards. They can also be used for production of chemicals and as fuel for generation of steam and power.

The economic use of these important renewable resources has been neglected in most countries in the past. However, as their value becomes increasingly recognized for a multiplicity of uses, they represent a substantial potential source of renewable raw material for the future.

As an indication of the huge requirements for renewable fibrous resources for pulp and paper alone, predictions of the amount of paper and paperboard consumed in future years are summarized in Fig. 1. Knowledge of the present world situation on all raw materials suitable for pulp indicates that the upper limits of the range of anticipated possible consumption levels will never be reached, unless there is a complete breakthrough in finding an inexpensive and limitless source of power and unless a crash program is begun immediately in all areas of the world to develop forests and crops capable of producing enough fiber by that time.

Even with all new measures to increase the availability of wood we cannot afford to neglect other fibrous sources such as recycled wastepaper and greater utilization of the renewable nonwood plant fibers. The continuing downward trend in wastepaper recycling, reaching the level of about 20 percent of the overall fibrous furnish for paper and paperboard in the United States in 1969, could be reversed to meet goals of 25 to 27 percent by 1985, 30 percent by 1990, and up to at least 35 percent by the end of the century. Some countries have already achieved a use rate of 35 percent wastepaper in the overall papermaking furnish (*1*). However, this will not eliminate the critical need for ever-increasing amounts of virgin fibrous raw materials for pulp and paper, including the use of agricultural residues and other nonwood plant fibers.

Present and Potential Use of Nonwood Plant Fibers Worldwide

Although the nonwood plant fibers are used now to only a limited extent in North America and Europe, they represent one of the major sources of fibrous raw material for many of the developing countries of the world. Their importance promises to become greater to many of the developed countries as well, and the pulp and paper industry worldwide should become familiar with the merits of some of these fibers.

These fibers include:

1) Agricultural residues such as sugar cane bagasse, cereal straw, sorghum, and rice straw.

2) Natural growing plants such as bamboo, reeds, papyrus, esparto grass, and other grasses, any of which might also be grown as crop fibers.

3) Nonwood crop fibers which are grown primarily for their fiber content. This last group includes (i) bast fibers or stem fibers, including jute, hemp, kenaf, ramie, crotalaria (or sunn hemp), okra, flax tow, and old rope or rags made from such fibers; (ii) leaf fibers such as abaca (manila hemp), sisal, and henequen; and (iii) cotton fibers, cotton linters, and cotton rags.

Although these nonwood fibers now constitute only about 5 percent of the raw material used for pulp and paper on a worldwide basis, and only about 1 percent in North America, they are particularly important for the developing countries in the Middle East, Asia, parts of Africa, and Latin America. In these areas, the output of nonwood plant fiber pulp has actually been increasing faster than the output of wood pulp. In some countries, and even entire regions, nonwood pulps represent more than 50 percent of the overall fibrous furnish for paper and paperboard.

At the 1973 Nonwood Plant Fibers Conference of the Technical Association of the Pulp and Paper Industry (TAPPI), Atchison (*2*) presented a detailed worldwide review of the present status and future potential for these raw materials. An up-to-date summary of the pertinent statistics and information relative to their use is included herein.

Present and Potential Use of Sugar Cane Bagasse

Of the many nonwood fibers considered or utilized for pulp manufacture, bagasse, more than any other, promises to become the first major fibrous raw material. It is readily available and easily accessible in many countries and, fortunately, is abundant in some wood-poor countries.

From the standpoint of practicality, bagasse is by far the most important nonwood plant fiber. This is easy to understand, since before its use as a fiber source it has already been used to produce 5 to 10 metric tons of sugar per hectare (2.2 to 4.5 short tons per acre). This has carried the rent of land and the costs of growing, harvesting, transporting, and processing the cane. Relatively little additional preparation—only moist and wet depithing—is required before it is ready for the pulp digester. And it is readily available to the pulp mill at the sugar mill conveyor at a cost only slightly higher than that of replacing the bagasse in the sugar mill boilers with fossil fuel. None of the other nonwood plant fibers matches its economic advantages.

During the past 25 years, technical and operating progress in bagasse pulping has been very rapid; it now equals that for wood pulp mills. There are now no technical or operating problems to prevent a rapid expansion in the use of bagasse for pulp. The major economic problem is the cost of fossil fuel to replace the bagasse now used for fuel at the sugar mill and the extra fuel needed for pulp manufacture as compared with that for wood pulp. The other fuel would have to be imported by some coun-

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tries. But this factor will diminish in importance as pulpwood and wood residue costs increase all over the world; this will be true particularly if the countries with bagasse would otherwise have to import pulp and paper at high prices corresponding to those for oil. Also, the manufacture of paper from pulp from local bagasse and imported long-fibered pulp and fuel is generally favorable for the consuming country. This results in a reduction of foreign exchange paid out and provides local employment of capital, labor, and other resources, usually at a lower total cost for the product than for imported paper.

It was not until 1939 that the first three successful bagasse pulp mills began operations: one in Peru, one in Taiwan, and one in the Philippines. Progress at first was very slow, and by 1950 there were still only five or six mills in the world based on utilizing bagasse, with a total production capacity of less than 100,000 metric tons. By 1968, total bagasse pulp production had increased to about 500,000 metric tons, and in 1973 bagasse pulp production exceeded 1 million metric tons. This appears small in comparison to production of wood pulp, which was about 113 million metric tons in 1973, or the total production of pulp including nonwood plant fiber pulp, amounting to 120 million metric tons in 1973. However, on a percentage basis the use of bagasse as a raw material for pulp and paper has increased more since 1950 than the use of any other fibrous raw material.

At the present time, there are more than 30 bagasse pulp mills with daily capacity of more than 30 metric tons. For many of these, daily capacity is in the range of 100 to 150 metric tons, and for some is as high as 250 metric tons. In addition, there are at least 50 small bagasse pulp mills with daily capacity of 10 to 25 metric tons. Altogether, bagasse pulp is produced in 22 countries. At the present time one new bleached market pulp mill for production of 300 metric tons per day is under construction in Taiwan, and a bagasse newsprint mill for production of 300 metric tons per day is under construction in Peru. Many other large mills with capacity of 200 to 350 metric tons per day are being planned or considered all over the world, primarily in the wood-poor countries.

A wide range of types of bagasse pulp are now produced. These vary from the mechanical type pulp of very high yield, used for insulation board, to the highest quality, high-brightness bleached bagasse pulp used for high quality tissue, printing, and writing papers and bleached paperboard.

Bagasse pulps are now used in practically all grades of paper, including bag, wrapping, printing, writing, toilet tissue, toweling, glassine, corrugating medium, linerboard, bleached boards, and coating base stock. Sugar cane bagasse has great potential for the future as a renewable fibrous resource.

Present and Potential Use of Cereal Straws and Rice Straw

Straw is the most abundant of all of the nonwood plant materials. Great quantities of this renewable resource are available all over the world. Prior to World War II, there were a number of strawboard mills in the U.S. Midwest. However, these have either closed or have switched over to wastepaper or semichemical hardwood pulp for corrugating medium and to wastepaper for combination board. The changing agricultural pattern, with wheat being grown farther west, greatly increased the collection area and the transportation costs to the existing mills. The use of straw became uneconomical, and wastepaper and low-cost hardwoods were substituted as raw material.

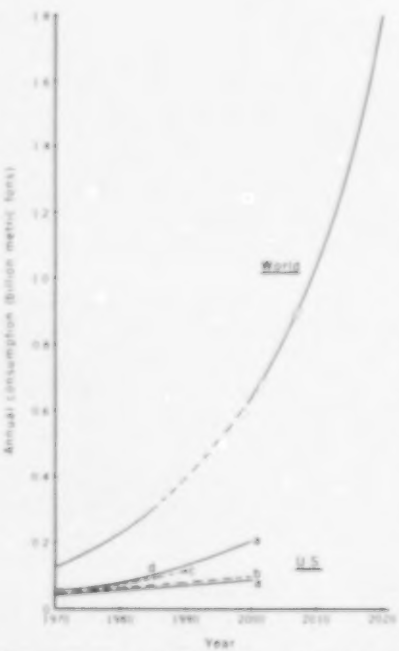

Fig. 1. Predictions for U.S. and world future annual consumption of paper and paperboard. Sources for predictions are as follows: United States: (curve a) Resources for the Future, Inc., Washington, D.C.; (curve b) *U.S. Forest Resource Report No. 17* (Department of Agriculture, Washington, D.C., 1965); (curve c) B. Slatin, *Tappi* **55**, 499 (1972); (curve d) D. Moore, in *U.S. Forest Resource Report No. 18* (Department of Agriculture, Washington, D.C., 1967). World Projections: 1970–1985, U.N. Food and Agricultural Organization (1971); 2000–2020, *Papir a Celuloza* (1972). In 2020 world average use is estimated at 182 kilograms per capita per year.

It is still economical or of national interest, however, to use cereal straw and rice straw in many other countries. They are now being used in 35 countries for production of pulp, and several new large straw mills are being built. Total production of straw pulp on a worldwide basis has remained relatively constant at about 1.36 million metric tons (1.5 million short tons) annually. However, with changing economic conditions a further increase in the use of straw is predicted.

By using better collection methods, the total worldwide straw potential could exceed 1 billion metric tons, of which 100 million metric tons might be collected in the United States alone. Even if 10 percent of the world's straw were used for pulp production, this could mean more than 30 million metric tons of pulp worldwide and more than 3 million metric tons in the United States alone. Greater use of this resource awaits only the economic necessity.

If there is to be any substantial increase in the use of straw in the United States, greater efforts must be made to develop more economical methods for straw collection, handling, transportation, and storage, so that the price of straw to the mill will be more competitive with that of other raw materials such as hardwoods. If strenuous efforts are made in this direction, straw may once again find use in the centers of the wheat-growing areas such as the Dakotas, Kansas, and Nebraska.

Great changes in collection, handling, and storage methods are probably possible along the lines of bulk storage of bagasse and bulk handling and storage of chips. By completely eliminating the baling of straw and handling it entirely in bulk, it is believed that costs might be decreased drastically. Now may be the time to get started on a project toward greater utilization of this valuable resource, which is renewed annually.

Use of Bamboo

Bamboo was first utilized for papermaking in China centuries ago by crude extraction methods. It is still one of the major fibrous raw materials of the People's Republic of China, with bamboo production estimated at 550,000 metric tons in 1972.

Modern-day interest in bamboo utilization appeared in India 55 years ago, and commercial application started about 45 years ago. The world's modern bamboo pulp and paper industry is still centered in India, where 70 percent of the total pulp produced is made from bamboo in about 20 mills. Total bamboo pulp production in India in 1972 is estimated at 550,000 metric tons.

Table 1. Estimated world capacities and production of paper and paperboard compared to estimated capacities and production of nonwood plant fiber pulps in 1972. ADMT, air-dry metric tons.

Area	Paper and paperboard production capacity* (1000 ADMT)	Paper and paperboard production† (1000 ADMT)	Paper-grade nonwood plant fiber pulp production capacity* (1000 ADMT)	Paper-grade nonwood plant fiber pulp production† (1000 ADMT)	Nonwood plant fiber pulp in overall furnish† (%)
North America	66,027	59,424	1,000	450	0.8
Latin America	4,947	4,452	639	575	12.9
Western Europe	41,246	37,121	1,148	1,030	2.8
Eastern Europe	5,099	4,589	251	225	4.9
U.S.S.R.	9,800	8,820	850	480	5.4
Africa	1,144	1,029	160	131	12.7
Near, Middle East	567	510	67	50	9.8
Japan	15,609	14,048	6	6	
People's Republic of China	4,450	4,005	2,400	1,900	47.4
Asia, Far East	2,963	2,667	1,326	1,190	44.6
Oceania	1,855	1,670	3	3	0.2
World total	153,707	138,335	7,850	6,[illegible]‡	4.4

*Estimates by U.N. Food and Agricultural Organization. †Estimates by Joseph E. Atchison Consultants, Inc., based on production data from many sources. ‡In addition to the paper grade pulp, about 270,000 ADMT of dissolving grade pulp is manufactured from cotton linters, making a total of 6,310,000 ADMT of nonwood fiber pulp.

Small bamboo pulping installations also exist in Burma, Thailand, Pakistan, Indonesia, Bangladesh, Taiwan, the Philippines, and Brazil. Additional mills are being considered in other countries such as Burma and certain areas of Africa, where there are tremendous unexploited stands of bamboo. It is estimated that the total world-wide production of bamboo pulp in 1972 was about 1,360,000 metric tons, including that of the People's Republic of China.

The properties of bamboo kraft pulp—relatively high tear but low tensile strength—make it particularly suitable in blends with pulps of lower tear but higher tensile strength, such as those from hardwood and bagasse; the blends provide a useful balance of strength and other properties for many grades of paper.

Unfortunately, entire native bamboo stands have a tendency to flower unexpectedly, seed, and die. As several years are required to reestablish the bamboo stand, any mill relying on bamboo must choose plantation species with the longest period of preflowering maturity. However, a gradual increase in the use of bamboo as a source of pulp, is believed likely, especially in the developing countries where it will be grown as a crop fiber.

Reeds as Raw Material for Pulp

Huge quantities of reeds grow in the saltwater delta areas of many rivers in eastern Europe, Africa, and Asia. The major reed (*Phragmites communis*) grows stalks 3 to 4.5 meters high and 2.5 centimeters in diameter. It has had only limited use for pulp until recently, because of the problems of harvesting the stalks.

In view of the vast quantities of this raw material available annually and its suitability for a soft and bulky pulp for printing papers, improved and less costly collecting and harvesting procedures will probably bring about increased utilization in future years.

An extensive experimental program is presently under way in southern France on the cultivation of another reed—*Arundo donax*—in large plantations to supplement the limited supply of hardwoods in a region with existing pulp mills.

Papyrus as a Pulp Source

In ancient times papyrus paper was made in Egypt from the pith of the paper reed (*Cyperus papyrus*) growing in the shallow waters of the Nile River. The rind of the stalk, which actually contains the good papermaking fiber, was removed from the core of pith. The core was then sliced into thin strips, which were laid parallel in crossing layers under a cloth and pounded with a mallet into a unified sheet. Drying the sheet in the sun caused the pith cells to collapse and the layers to stick together. After that the surface was smoothed with a polished stone, and scrolls were formed by joining several sheets end to end. This product was used in and exported from Egypt from the 5th century B.C. to the 4th century A.D., when it was replaced with parchment.

At the present time papyrus grows in the lakes and rivers of many areas of Africa, the Middle East, and South America. Huge quantities can be found in the upper Sudan, where a number of promotional efforts have been made over the years to develop a paper industry based on the raw material. One mill was built on the upper Nile before World War II, but it was not successful and was abandoned.

Papyrus is somewhat similar to bagasse in that it contains about 35 percent pithy material and 65 percent good rind fiber suitable for production of high quality bleached pulp. However, the technical problems of removing the pith and the economic problems of harvesting the stems in the swamps and transporting raw material containing 90 percent water appear to represent almost prohibitive obstacles to developing a paper industry based on papyrus.

Esparto Grass and Sabai Grass

Esparto grass grows in the wild state over fairly extensive areas in North Africa and also in southern Spain near Almeria. The plant occurs as a coarse, strong grass which is actually a long, rolled-up leaf in a sheath. It grows to 1 meter in height in clumps of 0.3 to 0.6 meter in diameter. The grass is harvested by hand pulling so as to leave the root intact for regrowth. The grass is harvested over a 4- to 6-month period between August and April.

Esparto grass has been used for production of high quality bleached pulp for more than 100 years, and it has some special properties such as high opacity, good bulk, excellent dimensional stability, and good printability. There are esparto pulp mills in France, Spain, Algeria, and Tunisia, and one is being considered in Morocco. However, the total amount of esparto grass available on an annual basis is only about 500,000 metric tons, so that the maximum potential pulp from the source is only about 200,000 metric tons.

Sabai grass, which has some of the desirable characteristics of esparto, is used to a very limited extent in both India and Pakistan.

Leaf Fibers

The leaf fibers, such as sisal, abaca, and henequen, have found very little use in the pulp and paper industry, except on a small volume for specialty grades. Although the pulp produced from some of these fibers, such as abaca, has outstanding qualities, the cost of growing, harvesting, handling, and pulping these materials is extremely high. Therefore, it appears that their use in the pulp and paper industry will remain very limited.

Use of Kenaf and Other Bast Fibers or Stem Fiber Plants

The bast fibers that are found in bark of the stems of such plants as jute, true hemp, kenaf, ramie, crotalaria (sunn hemp), okra, and roselle have also not found great use in the paper industry because of their high cost. Only the bast fiber has been used, and the core material, representing about 60 to 65 percent of the total dry weight of the stalk, has been discarded.

In recent years, however, kenaf has emerged as a stem plant fiber which appears to have great potential. Much research has been done by the U.S. Department of Agriculture during the past 10 years on both the cultivation of this plant and its utilization for manufacture of pulp and paper.

As a result of the recent shortage of pulp and its extremely high price in the world market in 1973 and 1974, interest in kenaf has spread all over the world. There is no doubt that kenaf and some of the related species of bast fiber plants, such as roselle and crotalaria, will soon find widespread use in the pulp and paper industry.

Here again, some concentrated well-financed efforts will have to be devoted to the problems of harvesting, handling, storing, and processing the kenaf stalk before it or its two components, long and short fiber, go to the digester. However, when it is considered that growth rates of 15 to 25 metric tons of dry stalk material per hectare (6 to 10 short tons per acre) have been achieved in good growth areas, this renewable resource certainly merits the continued concentrated efforts required to make its use a commercial reality.

Present Production of Pulp from Nonwood Plant Fibers

To put the importance of the nonwood pulp into proper perspective, consider the U.N. Food and Agricultural Organization world capacity estimates for total paper and paperboard for 1972 in the various regions of the world as compared to the capacity estimates for nonwood plant fiber pulp. This comparison gives an indication of the percentage of nonwood fiber pulp used in the furnish in various regions. These data are shown in Table 1 along with estimates of actual production levels in each area for 1972 and the percentage of nonwood fiber pulp used in the furnish in each region.

For the entire Far East and Asia, including the People's Republic of China, nonwood plant fibers play an extremely important role, with the area as a whole using almost 50 percent nonwood fiber pulp in the total furnish. In Latin America, Africa, the Near East, and Middle East, the percentage varies from 9.8 to 13.5 percent. By contrast, the use of nonwood plant fibers in Japan and Oceania is almost nil, and in North America they represent less than 1 percent of the total fibrous furnish (Table 1).

For the United States specifically, an estimate of the total consumption of nonwood plant fiber pulp for paper and board, including high-yield bagasse pulp for insulating board, is given in Table 2. In addition to the nonwood fiber pulp produced for papermaking in the United States, about 130,000 short tons of cotton linter pulp are produced for dissolving pulp, some of which is exported.

Table 2. Estimated total nonwood plant fiber pulp consumption in the United States in 1972 for paper and board

Item	Amount consumed (metric tons)
Bleached bagasse pulp	36,300
High-yield mechanical type bagasse pulp for wallboard	181,500
Cotton linter pulp	45,400
Rag pulp (bleached)	45,400
Flax pulp	36,300
Abaca pulp	14,500
Rag pulp for roofing felt	99,400
Total	453,800

Table 3. Estimates of total production of various nonwood plant fiber pulps in 1972.

Raw material	Estimated world production of pulp (1000 ADMT)	Estimated U.S. production of pulp (1000 ADMT)
Cereal straw, mainly wheat and rye	1,360	
Rice straw	630	
Bamboo	1,360	
Bagasse	915	218*
Reeds	270	
Cotton linters, both paper grade and dissolving pulp	330†	160†
Esparto and sabai grass	110	
Rags, abaca, flaxseed straw, hemp, sisal, and other nonwood plant fibers	1,335	187
Estimated total nonwood plant fiber pulp production	6,310	565

*U.S. bagasse pulp production includes high-yield pulp for wet process insulating board production. †U.S. cotton linter pulp production includes 115,000 ADMT for dissolving pulp and 45,000 ADMT for papermaking. World cotton linter pulp production includes about 270,000 ADMT for dissolving pulp and 60,000 ADMT for paper grade pulp.

Nonwood plant fibers are presently playing a very minor role in North America. In fact, there has been practically no increase in their use over the past 10 years. This has also been true of Europe, Japan, and Oceania. However, in the case of Latin America, the use of nonwood plant fiber pulp has approximately doubled in the past 10 years. In Africa, the Near East, and Middle East, it has approximately tripled between 1962 and 1972, and in the Far East excluding Japan, the increase for the 10-year period has been on the order of 70 percent, or an annual average of 5.5 percent compounded annually.

Table 3 shows an estimate of the total production of each of the nonwood plant fiber pulps in 1972, both on a worldwide basis and for the United States separately. It can be seen that straw, bamboo, and bagasse are the leading nonwood plant fibers now in use.

Yields of fiber per hectare for nonwood plant fibers used in papermaking are given in Table 4, along with the estimated equivalent amounts of bleached pulps that could be produced from them.

Total Worldwide Availability of Nonwood Fibrous Raw Materials

From data the total worldwide production of agricultural crops and the acreage planted in each crop, it is possible to make reasonably accurate estimates of the total amount of each type of residual fiber that might be collected in each country. Similarly, for fibrous crops that are grown specifically for the fiber content, it is possible to make accurate estimates of total availability. However, in the case of wild-growing raw materials such as reeds and bamboo, such estimates are far more difficult, and accurate data are not available.

The estimates in Table 5 give a reasonably good indication of the tremendous quantities of these nonwood plant fibers which can become available if they should be needed as raw materials in papermaking. The estimated total exceeds 1 billion metric tons of fibrous raw material, of which only a small fraction is being used.

Straw has the greatest overall potential if only quantity is considered. Furthermore, this potential can easily be increased to more than 1 billion metric tons if efficient and economic bulk handling and storage methods are developed.

From an economic standpoint, however, it is believed that bagasse will continue to lead all other nonwood plant fibers for the medium-term future. It promises to become a major papermaking pulp during the 1970's and 1980's, and may represent 2 to 3 percent or more of the world pulp pro-

duction of 220 million metric tons expected by 1985, as compared to less than 1 percent of world production at the present time. By 1985, it is expected that total nonwood plant fiber pulp production will amount to 7 or 8 percent of total world pulp production as compared to less than 5 percent at present.

To summarize the nonwood plant fiber picture, there is no doubt that the nonwood plant fibers will play an increasing role in the world's pulp and paper industry. It appears that the necessary fibrous resources either exist already or can be grown in the developing countries to sustain the increasing pulp and paper requirements in these areas. Furthermore, some of these areas will become net exporters of nonwood pulp, especially bagasse pulp, even to the highly developed countries such as Japan and Western Europe.

Conclusions About Future Use of Nonwood Fibers

The world's pulp and paper industry, as well as the forest products industry in general, is becoming more and more concerned about its future sources of fibrous raw material. Already we see massive movement of pulpwood chips over long distances by sea, and this practice will undoubtedly expand greatly in future years. Many large-scale plantations of fast-growing pine and hardwoods in the tropical areas are being developed. Some giant projects in Brazil for growing eucalyptus have already gotten under way.

The mixed tropical hardwoods are also being considered seriously as a raw material for pulp and paper. Some mills are already using these woods successfully for a variety of paper and paperboard products ranging from newsprint to linerboard. Other large-scale projects based on mixed tropical woods are under development.

There appears to be no question that nonwood fibers will play an increasing role in satisfying the world requirements for fibrous raw material. More than 1 billion metric tons of such material could be made available, and even greater quantities could be grown if necessary.

By properly selecting the appropriate mixture of nonwood fibers, and the appropriate pulping processes, any grade of paper and paperboard can be produced. If circumstances require, all grades can be produced without the addition of any wood pulp. In fact, some grades are already being produced with 100 percent nonwood fibers. However, in most cases, it is expected that nonwood fibers will be used in blends with at least a small proportion of wood pulp.

Bagasse will undoubtedly be in the forefront, as it has been over the past 18 years. Already, several large bleached bagasse market pulp mills for production of high-brightness pulp are either under construction or in advanced planning stages. These include a bleached bagasse market pulp mill in Peru with capacity of 350 bone-dry metric tons (BDMT), which is being developed by Industrias del Peru, and a 300-BDMT-per-day bleached bagasse market pulp mill in Taiwan being constructed by Taiwan Sugar Corporation.

Other large bagasse market pulp mills are being considered in the Philippines, Australia, Mexico, Peru, Hawaii, the Caribbean area, and South Africa. In addition, many expansion programs are under way at existing bagasse pulp and paper mills all over the world, and many new integrated projects are either under construction or are being seriously considered, including bagasse newsprint projects, each with capacity of 300 ton/day, in Peru and Mexico and a 300 ton/day integrated bleached bagasse pulp and paper mill in Cuba.

Furthermore, large-scale expansion programs are being developed for utilization of bagasse for production of fiberboard and particleboard, including three projects in Cuba, each with production capacity of 100 ton/day.

It seems almost inevitable that straw, with its enormous supply potential will eventually reemerge as a major raw material, whether for pulp, chemicals, or even fuel. Potential economic advantages of its use will sooner or later lead to the required development work on collection and storage. Just recently, contracts have been signed for a 120 ton/day bleached straw pulp and paper mill in Syria and a 200 ton/day mill in Turkey. Kenaf and other straw fibers also have great potential for the future as the remaining problems are gradually solved.

Table 4. Estimated annual collectable yields of various nonwood plant fibrous raw materials per hectare; BDMT, bone-dry metric tons.

Raw material	Estimated collectable fibrous raw material (BDMT per hectare)	Estimated equivalent in bleached pulp (BDMT per hectare)
Sugar cane bagasse	5.0 – 12.4	1.7 – 4.2
Wheat straw	2.2 – 3.0	0.7 – 1.0
Rice straw	1.4 – 2.0	0.4 – 0.6
Barley straw	1.4 – 1.5	0.4 – 0.5
Oat straw	1.4 – 1.5	0.4 – 0.5
Rye straw	2.5 – 3.5	0.8 – 1.0
Bamboo, natural growth	1.5 – 2.0	0.6 – 0.8
Bamboo, cultivated	2.5 – 5.0	1.0 – 2.1
Reeds, U.S.S.R.	5.0 – 9.9	2.0 – 4.0
Kenaf, total stem weight	7.4 – 24.7	3.0 – 9.9
Kenaf bast fiber	1.5 – 6.2	0.7 – 3.2
Crotalaria bast fiber	1.5 – 5.0	0.7 – 2.5
Papyrus, upper Sudan	20.0 – 24.7	5.9 – 7.4
Abaca (manila hemp) fiber	0.7 – 1.5	0.4 – 0.7
Flaxseed straw	0.5 – 1.0	0.09 – 0.17
Cotton staple fiber	0.3 – 0.9	0.25 – 0.86
Second-cut cotton linters	0.02 – 0.07	0.015 – 0.062

Table 5. Estimated availability of specific nonwood plant fibrous raw materials, 1972. Values are for potential availability with present collection methods.

Raw material	World-wide (1000 BDMT)	Continental U.S. (1000 BDMT)
Sugar cane bagasse	55,000	1,600
Wheat straw	550,000	50,000
Rice straw	180,000	1,000
Oat straw	50,000	8,000
Barley straw	40,000	5,000
Rye straw	60,000	2,000
Flaxseed straw	2,000	500
Grass seed straw	3,000	1,000
Subtotal, straw	885,000	67,500
Bast fibers		
Jute, mainly from India and Bangladesh	4,425	
Kenaf and roselle, mainly from India and Thailand	1,674	
Subtotal, bast fibers	6,099	
Leaf fibers		
Sisal	648	
Abaca	92	
Henequen	164	
Subtotal leaf fibers	904	
Reeds	30,000	
Bamboo	30,000	
Papyrus	5,000	
Esparto grass	500	
Sabai grass	200	
Total, cotton staple fiber	13,500	3,000
Total, second-cut cotton linters	1,000	250
Estimated total	1,027,203	72,350

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Potential for Converting Wood into Plastics

Chemicals from wood may regain importance as the cost of petroleum continues to rise.

Irving S. Goldstein

Recent increases in the price of petroleum and concern about its availability at all have stimulated interest in using renewable resources in its place. This study attempts in a preliminary way to consider the use of wood including wood residues as a raw materials base for synthetic polymers. Wood is our most abundant renewable resource and has the additional advantage over annual vegetation that most of the biomass resulting from the conversion of solar energy is stored in the tree, often for scores of years, until it is harvested.

Chemicals from wood is not a new concept. The destructive distillation of wood to charcoal is an ancient art, and until recently the controlled thermal degradation of wood by pyrolysis and distillation was used as a source of chemicals. However, during this century fossil materials such as coal, oil, and natural gas have become more convenient sources of chemicals. Current economics favors petroleum, although we may eventually return to our renewable resource—wood—as the raw material of choice.

Despite the fact that most of the synthetic organic chemicals produced for use as solvents, polymers, plastics, and chemical intermediates are petroleum based, chemicals from wood, or silvichemicals as they are sometimes called, are still derived in large quantity. Table 1 lists those which are in commercial use.

Most important in this compilation is our most widely used polymer, cellulose, which is for the most part used in its natural fibrous state after extraction from the wood. However, chemically modified derivatives of cellulose such as cellulose acetate and rayon also amount to billions of pounds.

A considerable research effort has been directed for many years toward the production of greater quantities of chemicals and polymers from wood (*1*, *2*). However, with the exception of periods of national emergency in several countries there have been no full-scale commercial plants operated outside of the U.S.S.R. Industrial chemicals from wood *have* found a place in the controlled economy of the U.S.S.R.

In the rest of the world the trends during the past decade until 1973 have been much stronger in the opposite direction, with the cost of petrochemicals continuing to decline while the cost of wood continued to rise. These trends led to such effects as the virtual discontinuance of research on chemical utilization of wood in the United States and the development of petrochemical based polymers for synthetic pulp, which, although useful for their inherent properties by themselves, were being talked about as replacements for cellulose on a lower cost basis.

It has now become apparent that this price trend was temporary, and that ultimately the true cost of a limited exhaustible material will become greater than that of a renewable resource. We can continue to enjoy inexpensive petroleum at a price based only on low extraction costs plus an arbitrary profit margin only as long as the supply lasts or other countries are willing to sell it to us. Eventually we will have to rely on another source of carbon for our organic materials because petroleum will have become either exhausted or so scarce that it will be too expensive.

Of the alternative carbon sources coal and wood, coal is also a finite resource and will ultimately be consumed leaving only wood as a renewable resource in perpetuity. Extraction costs and transportation costs for coal are higher than for petroleum and costs to repair and prevent environmental damage are also considerable. Just as the cost of oil has not reflected the depletion of the resource, the cost of coal has not reflected environmental damage. Chemicals from wood appear to have a better competitive chance against coal-derived chemicals than against the artificially priced petrochemicals. Research on coal chemicals has also been neglected.

The objective of this article is to provide a perspective on the suitability of wood as a chemical raw material for plastics and for production of polymers. For this purpose sufficient wood must be available, suitable processes for conversion must be on hand or developed, and the costs must not be unreasonable.

Availability of Wood

In 1974 the total U.S. production of plastics, noncellulosic synthetic fibers, and synthetic rubber amounted to almost 37 billion pounds or over 18 million tons. These materials are broken down by categories in Table 2, which also shows the amount of lignocellulose raw material from wood needed to produce the various synthetic polymers estimated from optimistic approximate yields of the monomers obtainable from the wood. About 95 percent of the total polymers produced are conceptually derivable from wood, although the multiple process steps required for some would militate against the exploitation of this source. The amount of lignocellulose required would be just under 60 million tons. Interestingly enough the ratio of the two major wood components, cellulose and lignin, which would be needed is about 2 : 1, which is the same as their natural abundance in the wood.

In 1974 the estimated total wood pulp production in the United States was just under 50 million tons; this amount required about 100 million tons of wood at 50 percent yield. The wood needed for chemical conversion to polymers, therefore, would amount to 60 percent of that now being used for pulp.

Although wood for pulping must meet certain requirements such as species suitability for pulping, fiber length, and fiber morphology, wood destined for chemical utilization need not. Consequently, large quantities of wood unsuitable for pulping or conversion into solid wood products would be suitable for chemical processing. The demand for wood for chemicals would be modest compared to other wood uses and could be filled from sources not suitable for other uses.

In 1970 wood residues at primary manufacturing plants amounted to 15 million tons and logging residues to about 50 mil-

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lion tons (*3, 4*). Supplies of hardwood timber are increasing although material suitable for high quality uses is limited. Fortunately, chemical conversion can utilize the small tree sizes and the species for which other markets are limited. In 1970 there was an excess of 70 million tons of net annual growth over removal of hardwoods (*4*).

A further source of wood for the production of chemicals could result from the clearing of cutover land now containing only cull trees in connection with reforestation with the supertrees now being developed by genetic improvement. Considering only poor sites now containing hardwoods which would be more productive in pine, a conservative estimate for the Southern states alone would be 1250 million tons obtainable as a by-product of improved land management. Furthermore, the potential utilization of this "green junk" as it is alluded to by many foresters, could be the deciding factor in bringing about the use of the land for productive, managed forests that would meet our increasing needs for high-quality wood for lumber, plywood, and pulp.

An analogous situation applies in the Southwest where woody shrubs such as mesquite have invaded almost 100 million acres and compete with grass for scarce moisture. Removal of the mesquite, helped by a credit for its chemical utilization, would increase grazing capacity and have a positive effect on meat supplies.

It is obvious from these considerations that the wood needed for meeting our polymer needs should not seriously disrupt other demands on the forest resource for lumber, plywood, wood pulp, and the like; it could even increase the availability of these other products by supplying capital to hasten improved forest management.

Technical Feasibility

A common problem in elementary organic chemistry courses begins as follows: "Starting with coal, air and water synthesize the following. . . ." In a qualitative sense, therefore, wood as a source of carbon can be used to synthesize any organic material known to man. The technical processes discussed in this section are principally restricted, however, to those that retain to some degree the synthetic work already performed by the tree in converting carbon dioxide to more complicated molecules. Reversion of the wood to carbon monoxide or carbon dioxide would offer no advantage over the use of coal.

Wood is a mixture of three natural polymers—cellulose, lignin, and hemicelluloses—in an approximate abundance of 50 : 25 : 25, depending on species and other biological variation such as genetic differences within species and growing conditions. Cellulose and hemicelluloses are carbohydrate polymers that are built up from molecules of simple sugars. Cellulose is a long-chain polymer of glucose and differs from starch, which is also a glucose polymer, only in the way the glucose molecules are arranged. Hemicelluloses are shorter or branched polymers of five-carbon sugars (pentoses), such as xylose, or six-carbon sugars (hexoses) other than glucose. Lignin is a three-dimensional polymer formed from phenylpropane units which have grown into a complicated random large molecule with many different kinds of linkages between the building blocks.

In the production of wood pulp, the lignin, which acts as a cement between the cellulose fibers and as a stiffening agent within the fibers, is dissolved away by various chemical processes leaving the cellulose together with some remaining hemicelluloses behind in fibrous form. Some hemicelluloses are lost in the process because of their lower molecular weight and greater solubility.

Conversion to Gas or Liquid Feedstocks

Wood can be converted in very high yield to synthesis gas (carbon monoxide + hydrogen) by heating at temperatures up to 1000°C (*5*). This product can be readily converted to methanol. Small quantities of by-products useful in polymer synthesis are also generated. For example, from 3300 tons of wood per day the following are obtainable: ethylene, 172 tons; acetylene, 25 tons; propylene, 17 tons; benzene, 60 tons; and toluene, 9 tons. At these low yields about 150 million tons of wood would be needed each year to meet our ethylene needs for polymers alone.

Somewhat higher yields of unsaturated hydrocarbons in wood gasification have been reported when an electric arc at a temperature of 2000° to 2500°C is used. Acetylene has been obtained in yields of up to 35 percent (*6*), which would still require an excessively large wood supply.

Recent research at the U.S. Bureau of Mines (*7*) has successfully converted wood into oil that can be used as a liquid boiler fuel. Wood or other organic materials are reacted with carbon monoxide and water at 350° to 400°C at a pressure of 4000 pounds per square inch in the presence of various catalysts. Oil yields of 40 to 50 percent have been obtained. A pilot plant is under construction at Albany, Oregon.

This wood-to-oil process has implications for polymer synthesis in that the oil produced might be further converted to monomers in the same way that petroleum is processed. Since the oil still contains as much as 8 percent residual oxygen, conventional hydrocracking processes might not be effective because of the poisoning of catalysts by the water generated.

Conversion to Monomers for Conventional Polymers or Plastics

Of the 18 million tons of synthetic polymers listed in Table 2, 95 percent are derivable from ethylene (47 percent), butadiene (12 percent), and phenol (36 percent). These building blocks are all obtainable from wood. Ethylene and butadiene can be made from ethanol, which in turn can be made by fermentation of glucose, the hydrolysis product of cellulose.

$$\text{Cellulose} \xrightarrow{\text{hydrolysis}} \text{glucose} \xrightarrow{\text{fermentation}} \text{ethanol} \longrightarrow \text{butadiene or ethylene}$$

Phenol and related compounds are obtainable from the hydrogenation or hydrogenolysis of lignin.

$$\text{Lignin} \longrightarrow \text{phenols} \longrightarrow \text{phenolic resins, polyesters, and other aromatics}$$

Wood hydrolysis, the conversion of the carbohydrate polymers in wood to simple sugars by chemical reaction with water in the presence of acid catalysts, has been known for 150 years and has been practiced on a commercial scale in this country during World War I, in Germany during World War II, and is still in use in the U.S.S.R. The simple hydrolytic cleavage to sugars is complicated in the case of cellulose by its crystalline organization, which restricts the accessibility of the dilute acid to the bonds to be hydrolyzed. This resistance to hydrolysis requires the use of temperatures and acid concentrations which cause decomposition of the resulting sugars. Processes must balance rate of hydrolysis against rate of decomposition of the desired products (*1, 8, 9*). Glucose yields of approximately 50 percent of the weight of the cellulose have been attained.

Increasing this yield by rendering the cellulose more accessible to the hydrolyzing reagent would provide great economic benefits and warrants a high level of technical activity. The nature of the lignin residue is affected by the catalyst used and by the operating temperatures in the hydrolysis. It would be desirable to end up

with the most reactive lignin possible to allow its facile conversion to other useful products. The Udic-Rheinau process (*8*) utilizing strong hydrochloric acid as the catalyst does provide such a reactive lignin.

Conversion of cellulose to glucose by enzymatic hydrolysis using an enzyme from *Trichoderma viride* has received much attention at the U.S. Army Natick Laboratory. However, lignocellulose is resistant to the enzymes unless very finely ground or partially delignified. Other microbiological conversions of wood to useful chemicals are entirely possible, but have not advanced beyond the preliminary research stage.

Fermentation of the glucose solutions to ethanol is readily accomplished in yields of 85 to 95 percent by means of commercially proven techniques. The further conversion of ethanol to ethylene in 96 percent yield and to butadiene in 70 percent yield is also straightforward and was practiced on a commercial scale in the United States during World War II in plants that require much lower capital costs than those based on hydrocarbon conversion (*10*).

Phenolic products have been obtained from the lignin component of wood by various hydrogenation and hydrogenolysis techniques. Yields of 25 to 35 percent of monomeric phenols have been reported (*11, 12*) in pilot plant experiments, but verification on a commercial scale has not been attempted because of hitherto unfavorable economic comparisons with phenol production from petroleum.

Table 1. Silvichemicals of commerce (*18*).

Cellulose	Dimethyl sulfide
Cellulose esters	Dimethyl sulfoxide
Cellulose ethers	Kraft lignin
Rayons	Lignin sulfonates
Wood resin	Ethyl alcohol
Turpentine	Vanillin
Pine oil	Yeast
Tall oil	Charcoal
Tall oil rosin	Bark products
Tall oil fatty acids	Hemicellulose extracts

Polymers and Plastics from Macromolecules Present in Wood

The components of wood are already high polymers and can be utilized in that form without degradation to simple compounds and repolymerization. Most notable is the use of cellulose to the extent of almost 50 million tons per year, a quantity greater than the total of all synthetic polymers combined.

Cellulose derivatives such as rayon and cellophane (both regenerated celluloses), cellulose acetate, carboxymethylcellulose, and cellulose butyrate are important materials and could become even more important compared to completely synthetic materials as economic conditions change. Polymeric materials are marketed on the basis of cost and performance. The properties of cellulose derivatives may be modified and new derivatives developed—for example, by graft polymerization—to meet performance criteria at competitive costs. These shifts would probably occur in response to normal market influences.

The lignin component of wood may also be modified, esterified, etherified and condensed to change its physical properties. Furthermore, a relatively neglected major component of bark, polyphenolic acids, may be extracted in high yields and can be used in the preparation of resins, adhesives, and binders. Meeting adhesive and resin needs from this source would reduce the requirements for phenol.

New wood-based intermediates. The hemicellulose component of wood is much more readily hydrolyzed to simple sugars (pentoses) than the cellulose is to glucose. Prehydrolysis of the wood with a dilute acidic solution provides an aqueous xylose solution which can be further converted to furfural in 75 percent yield (*13*). Furfural can serve as a raw material for resins and adhesives and as an intermediate for the production of chemicals useful in making condensation polymers such as nylon. Furfural is now produced from corncobs and bagasse, but would be available in much greater yield from an integrated large-scale wood hydrolysis plant.

The glucose obtained from hydrolysis of cellulose instead of being fermented into ethanol can be converted into 5-hydroxy-2-furaldehyde which in turn is readily converted to levulinic acid (*14*). This material could well serve as an intermediate for a new family of polymers. Levulinic acid primarily for processing into diphenolic acid was produced commercially for a time in the 1960's, but the loss of the diphenolic acid outlet caused the venture to be abandoned.

New lignin-based intermediates. More complex molecules than simple phenols may be obtained from lignin by less drastic treatments than hydrogenation. For example, hydrolysis of alkali lignins under

Table 2. 1974 production of plastics, synthetic fibers, and rubber (*19*) and estimated lignocellulose raw material base required.

Material	Production (10^3 tons)	Lignocellulose required* (10^3 tons)
Plastics		
Thermosetting resins		
Epoxies	125	355 (L)
Polyesters	455	1,220 (L)
Urea	420	
Melamine	80	
Phenolic and other tar-acid resins	670	1,915 (L)
Thermoplastic resins		
Polyamide	100	285 (L)
Polyethylene		
Low density	2,985	11,530 (C)
High density	1,420	5,680 (C)
Polypropylene and copolymers	1,125	4,500 (C)
Styrene and copolymers	2,505	7,445 (L)
Polyvinyl chloride	2,475	4,225 (C)
Other vinyl resins	175	440 (C)
Total plastics	12,485	
Synthetic fibers		
Cellulosic		
Rayon	410	
Acetate	190	
Synthetic fibers (cont'd.)		
Noncellulosic		
Nylon	1,065	3,045 (L)
Acrylic	320	640 (C)
Polyester	1,500	4,020 (L)
Olefin	230	920 (C)
Total noncellulosic fibers	3,115	
Synthetic rubber		
Styrene-butadiene	1,615	5,700 (C), 1,920 (L)
Butyl	180	1,060 (C)
Nitrile	95	190 (C)
Polybutadiene	360	2,120 (C)
Polyisoprene	100	
Ethylene-propylene	140	825 (C)
Neoprene and others	280	
Total synthetic rubber	2,770	
Total plastics, noncellulosic fibers, and rubber	18,370	
Obtainable from lignocellulose	17,490	58,445
Cellulose derived (C)		38,240 (C)
Lignin derived (L)		20,205 (L)

*Estimated from optimistic approximate yields of monomers obtainable. (C) Cellulose derived; (L) lignin derived.

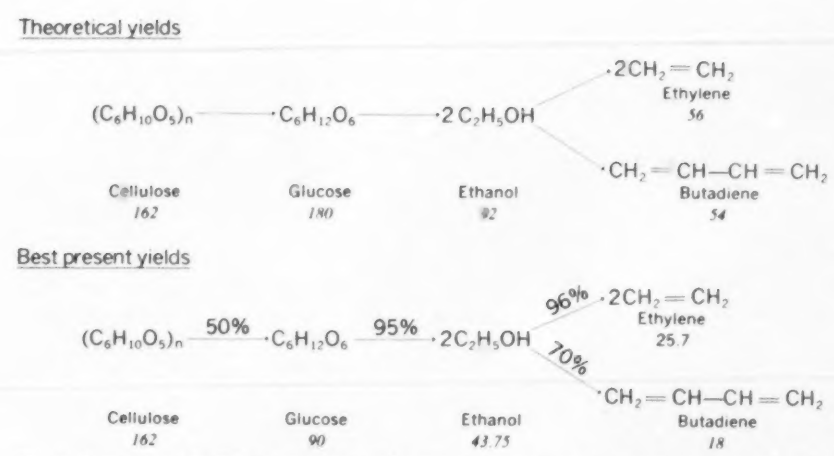

Fig. 1. Conversion of cellulose to ethanol, ethylene, and butadiene. The numbers in italics refer to molecular weights in the case of theoretical yields, and actual weights for best present yields. The same applies to Fig. 2.

neutral conditions gives yields of up to 25 percent of material with catechol (dihydroxyphenol) reactivity (*15*). These compounds could find useful applications in various resins. Other treatments of lignin might provide fragments with reactivity which would use even more of the lignin molecule.

Economic Opportunity

The preceding discussion on technical feasibility has indicated several areas where it would be highly profitable to devote further technical effort. The following seem especially important:

1) Conversion of viscous oxygen-containing oils from wood liquefaction into useful monomers.

2) Increasing the accessibility of crystalline cellulose to hydrolytic reagents to allow higher yields in wood hydrolysis.

3) Developing processes for the conversion of reactive lignins from wood hydrolysis to low-molecular-weight phenolic materials useful for polymer synthesis.

Chemical utilization of wood has progressed conceptually to a remarkable degree considering the relatively small research effort which has been devoted to it in comparison with the effort expended on petrochemicals during the past 50 years. An increase in the scale of wood research could be expected to provide commensurate further progress.

It is not possible with the data now available to provide a permanent and complete economic analysis of the relative costs of producing synthetic polymers from a wood and a petroleum base. Such calculations are also made difficult by the current flux in the costs of petroleum, other fuels, wood, plants, and capital. There is also the problem of internal accounting in which the internal transfer price of feedstocks affects petrochemical prices, and this is greatly influenced by the demand for and supply of gasoline and heating oil as well as by crude oil costs.

The published cost data cited below are now obsolete, but they are presented as points of reference to which escalation factors can be applied. Data for raw material costs alone are provided for ethylene, ethanol, butadiene, and furfural.

Wood costs. Exact figures for wood costs are difficult to assign. The cost of wood at the mill can vary from a negative cost for unusable residues which must be disposed of to as much as $40 per ton for quality hardwood sawlogs. Chipped wood can vary from $15 per dry ton from a total tree chipping operation to $25 per dry ton for bark-free pulp chips. For the purpose of this study a value of $20 per dry ton is assumed for wood suitable as a raw material for chemical conversion. With petroleum at $12 per barrel, wood has an equivalent value as fuel of about $20 per ton or 1 cent per pound compared to 3.8 cents per pound for the petroleum.

The cost of wood for producing a specific chemical also depends on the yield obtainable. Given the raw material at 1 cent per pound, a hydrolysis plant producing only glucose in 50 percent yield on cellulose would have a wood cost of 4 cents per pound of glucose (50 percent cellulose × 50 percent yield). However, if the plant were integrated to utilize the lignin and hemicellulose components as well, the wood cost per pound of glucose would be only 2 cents a pound. It is obvious that such integrated plants would be mandatory for a successful chemicals from wood scheme.

Gasification and liquefaction processes. Preliminary calculations provided in the 1971 report (*5*) concluded that the production of synthesis gas with some attendant yield of chemicals from lignocellulosic residues would require a raw material supply at a cost of only $2 to $5 per ton. The low yield of chemicals from this process plus the low likelihood of availability of the large tonnages of waste wood at such a low cost make it appear unpromising. The authors also estimated that acetylene production from wood (*6*) would not be economical because of the high temperatures and high voltage electrical energy required.

Perhaps the most complete cost figures obtainable for a wood conversion process are those developed for the Bureau of Mines liquefaction process (*7*). The operating costs for a 3000 ton per day wood waste plant with a capital investment of $51,000,000 (1973) would be $7.24 per barrel of liquid fuel produced at 50 percent yield. If the wood waste were free, this would be the entire cost of the product. If the wood cost were $20 per ton, the cost per barrel would increase to $15.64 [$8.40 wood cost for a 420-pound barrel (42 gallons at a density of 1.20) at 50 percent yield]. This range of $7 to $15 per barrel is certainly comparable to the present $11 to $12 price for some imported petroleum. The conversion of this liquid oil from wood to chemicals useful for synthetic polymers has not been studied, but at $15.64 a barrel or 3.9 cents per pound this synthetic oil with a density of 1.20 would cost the same for a raw material as crude oil with a density of 0.88 at $12 a barrel. High chemical yields (about 40 percent) would be needed to avoid excessive wood demands.

Ethanol, ethylene, and butadiene. Figure 1 summarizes the process steps and yields in these transformations. The first step in the production of ethanol from wood is the hydrolysis of cellulose to glucose. Hydration of the cellulose yields 180 pounds of glucose for each 162 pounds of cellulose hydrolyzed. If the glucose yield is 50 percent and the cellulose component of the wood costs 1 cent a pound, assuming utilization of the lignin and hemicellulose wood components, the material cost for glucose production would be 1.8 cents a pound. If the wood cellulose could be completely hydrolyzed to glucose in 100 percent yield, the material cost would be 0.9 cent a pound. Gross production costs for hydrolysis of waste to sugars were estimated in 1971 (*16*) at 1.65 to 2.08 cents a pound giving a total glucose cost of 2.55 to 4 cents a pound, depending on yield.

The hydrolyzate sugars in solution may then be converted to ethanol by fermentation. The cost of this fermentation is difficult to estimate since no large fermentation plants have been constructed recently in this country for the production of ethanol. Yields of 95 percent are obtainable.

Fermentation costs of 1.35 cents a pound were suggested in 1973 for a 250-ton-a-day plant (*16*), and could be as low as 1 cent a pound in a large installation. The cost of ethanol from glucose (87.5 pounds from 180 pounds at 95 percent yield) would then be 6.25 to 9.25 cents a pound or 41 to 61 cents per gallon. Material costs alone would be 3.7 cents per pound or 25 cents per gallon at 50 percent yield of glucose. The current market price for ethanol from petrochemicals is $1.15 per gallon for 95 percent (190 proof) alcohol.

The conversion of ethanol to ethylene in 96 percent yield has been performed commercially in this country, but not for the past 20 years. The plants have been dismantled and attempts to locate production cost data from old files have been unsuccessful. Since the process is simple, a production cost of 1 cent per pound might be assumed for the sake of argument. The cost of ethylene from ethanol (27 pounds from 46 pounds at 96 percent yield) would then be 11.7 to 16.8 cents per pound, depending ultimately on yield and production costs for glucose production from cellulose. Material costs alone would be 6.3 cents per pound at 50 percent glucose yield and 4.2 cents per pound at 75 percent glucose yield. The current published market price for ethylene is 11 to 11¾ cents per pound.

The conversion of ethanol to butadiene in 70 percent yield has also been performed commercially in this country, again not for over 20 years. In this case also, the plants have been dismantled and production costs have not been located. The process is reputed to require lower capital costs than other butadiene syntheses. Here we might assume a production cost of 2 cents per pound since two steps are required. The cost of butadiene from ethanol (37.8 pounds from 92 pounds at 70 percent yield) would then be 18.5 cents to 24.5 cents per pound, depending again on the cost of glucose. Material costs alone would be 9 cents per pound at 50 percent glucose yield and 6 cents per pound at 75 percent glucose yield. The current published market price for butadiene is 18 to 22 cents per pound.

These crude cost estimates indicate that the cost of ethanol, ethylene, and butadiene from wood might come within striking distance of the cost of these materials from petroleum. A more rapid increase in petroleum costs over wood costs might bring about a truly competitive situation or even a change in the raw material of choice.

Recent projections of the cost of ethylene and ethanol (*17*) based on naphtha reaching $124 to $136 per metric ton by 1977 place ethylene at 14 to 16 cents per pound and ethanol at $1.00 to $1.33 per gallon in 1977.

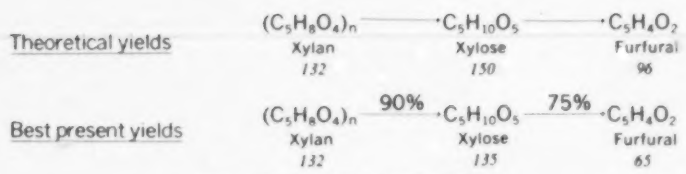

Fig. 2. Conversion of xylan to furfural.

Phenols and furfural. At the time that pilot plant studies were being carried out on the production of phenols by hydrogenation of lignin in 1966 (*11*), cost estimates indicated that a $6,000,000 plant could produce about 100,000,000 pounds of phenolic materials a year at a price of 9 cents a pound for phenol and 6 cents a pound for cresylic acids. Since synthetic phenol was then available at 7 cents a pound, a commercial plant was not built.

Today phenol has become both expensive and scarce. The published price is 27 to 33 cents per pound. Wood costs and plant costs have not risen that rapidly, and thus it appears that now a plant to produce phenols from lignin could be very profitable. Catechols can also be obtained from lignin (*15*) at a much lower cost than by synthetic methods starting with benzene.

When furfural was 11 cents per pound in 1961, a cost estimate for the production of furfural from xylose solutions from the hydrolysis of wood indicated a break-even price of 8.7 cents per pound (*13*). Now that the market price for furfural is 47 cents per pound, the economics for furfural production from wood in an integrated plant would be even more favorable. In the 1961 study the cost of xylose in solution was estimated at 2.3 cents a pound. In an integrated plant in which all the wood was used, the raw material cost per pound of furfural would be only 2 cents per pound.

Enzymatic processes. An alternative method of producing glucose is the enzymatic hydrolysis with cellulase. Economic analysis of the U.S. Army Natick Laboratory two-step process involving the culture of *Trichoderma viride*, followed by application of an enzyme-containing filtrate to the substrate, indicated a production cost of 5.3 cents per pound (*16*), somewhat higher than the acid hydrolysis cost estimates. Moreover, cellulose with a high lignin content is resistant to enzymatic hydrolysis, so wood would have to be partially delignified or finely ground to undergo hydrolysis by enzymes, adding additional processing costs.

Summary

The conversion of wood into chemicals for the production of most of our synthetic plastics, fibers, and rubbers is technically feasible. With refinements in technology a large integrated plant utilizing all components of the wood for production of ethanol (to be further processed to ethylene and butadiene), phenols and furfural would be approaching economic feasibility as well at current petrochemical prices. If crude oil prices continue to climb at a faster rate than wood costs, the economic feasibility of chemicals for polymers from wood would become certain.

Although technical feasibility has not been established, synthetic oils from liquefaction of wood might serve as feedstocks for cracking to chemicals in the same way that crude oil is presently used.

The fulfillment of all our polymer needs from wood as a raw material should not place an impossible burden on our wood supply, but might actually improve the availability of wood for lumber, plywood and pulp by providing a use for less valuable wood which would allow reforestation and improved forest management.

Since this article was first prepared in early 1975 it has become increasingly apparent that the economic feasibility of chemicals from wood will depend not only on their competitive position in relation to petrochemicals but also with respect to the chemicals which may become available from coal as coal conversion facilities are constructed to counter the shortages and high costs of petroleum.

Economic analyses of coal conversion schemes are abundant. There is need for similar studies on chemicals from wood, with continual updating as economic conditions change. Two such studies completed during the past year (*20*) are one by Pulp and Paper Research Institute of Canada which concluded that combined production of glucose, phenol, and benzene from wood could be profitable, and one sponsored by the U.S. Forest Service which has considered, among other things, the possibility of integrated plants producing ethanol, furfural, and phenol from wood.

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Renewable Resources for the Production of Fuels and Chemicals

Kyosti V. Sarkanen

In the future, mankind will make greater demands on renewable resources to satisfy needs for energy and carbon-based chemicals. This situation was envisaged as early as 1949 by Glesinger in his well-known book *The Coming of Age of Wood* (*1*). It can be readily demonstrated that the renewable biomass on our planet is quantitatively sufficient to supply the needs of the current world population. It can also be shown that we possess the needed chemical technology for the production from biomass of many of the commodities that we now produce from fossil fuels, such as fuel oil, gasoline, and synthetic polymers.

The scenario of total depletion of fossil fuel resources is an intriguing concept but not a useful one at the present time. As of now, there is a need for reducing the annual consumption of oil and natural gas, but not that of coal. This reduction may be accomplished in a number of ways; the substitution of renewable resources for oil and natural gas as a source of energy and chemicals is one.

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Table 1 is a comparison of the use of our dominant renewable resource, wood, with that of fossil fuels (oil, natural gas, and coal). The energy generation from wood includes that recovered from the waste of pulp mills. In terms of thermal units, it amounts to 1.1 quads (1 quad = 10^{15} Btu) (*2*). Compared with the total energy consumption in the United States, 68 quads in 1970, this is a rather small figure, but it exceeds that for nuclear energy (0.7 quad in 1974).

The total volume of wood products, 237 million metric tons, exceeds that of all synthetic polymers by 13-fold. Wood is the most extensively utilized raw material in the United States, also surpassing in volume all metals combined or the production of concrete. The energy requirements for its processing are low. It has been estimated (*3*) that the energy required to produce 1 ton of lumber in a conventional sawmill is 430 kwh, which may be compared with 2700 kwh for 1 ton of steel and 17,000 kwh for 1 ton of aluminum. The conversion of wood to paper products currently requires energy generated by fossil fuels. In the case of paperboard this amounts to 0.75 pound (1 pound = 0.45 kilogram) of fuel oil per pound of product. This compares favorably with the approximately 2 pounds of fuel required to produce 1 pound of synthetic polymer. Furthermore, current developments in the pulp industry suggest that the pulping and pulp bleaching operations can be made independent of outside energy sources by improving the conservation of energy in the process (*4*) and by better recovery of energy from the waste products.

It is thus obvious that extensive use is already being made of renewable resources, and the processing, in general, is not energy-intensive. It is consequently of great interest to investigate whether the utilization of renewable materials could be further expanded in order to conserve petroleum and natural gas. This could be done either by increasing the generation of energy from renewable resources or by the production, using renewable materials as feedstocks, of synthetic polymers. The potential of the second alternative is somewhat limited. Even complete replacement of synthetic polymers would save only 6 percent of the total consumption of oil and natural gas. Furthermore, two-thirds of this amount consists of processing energy that is replaceable by energy generated from coal. The realizable saving in feedstocks is thus limited to only 2 percent of the total volume of petroleum and natural gas.

Sources of Renewable Resources for Energy Generation

Vegetation biomass, including wood, has certain advantageous properties as fuel. The sulfur content is negligible (< 0.1 percent) in comparison with that of coal. Likewise, the ash content is reasonably low, and the recovered ash may be used as fertilizer. On a dry weight basis, the Btu

values of wood range from 8000 to 9000 in comparison with 18,000 for No. 6 fuel oil, 13,500 for bituminous coal, and 18,500 for natural gas. However, in contrast to fossil fuels, freshly cut wood has a high moisture content (40 to 150 percent on a dry weight basis), which reduces the heat value by as much as 20 percent. Thus, the net heat value of freshly cut wood is usually of the order 2500 to 3500 Btu per pound. Similar heat values are valid for agricultural residues as well.

Szego and Kemp (*5*) have proposed the establishment of special energy plantations to grow wood for the sole purpose of fueling large power plants. They estimated that it may be possible to convert, on perpetual basis, sufficient biomass from 370 square miles (1 mile = 1.6 kilometers) to fuel a 100-megawatt steam-electric plant. It has been pointed out (*2*) that, with the present growth rates, 2000 square miles would be a more realistic estimate for the required forest area. Apart from economic considerations, energy plantations would require enormous areas of land for any significant addition to energy supplies.

The concept of harvesting forest for the sole purpose of energy generation on a continuing basis may not be a realistic one in the United States, but it is worth exploring in the tropical countries where biomass production is more rapid and unused forest areas are still available. On a temporary basis, the principle could be applied for the rehabilitation of commercially unimportant hardwood forests to productive softwoods. Such areas exist both in northeastern and southern parts of the United States. Very recently, the energy potential of aquaculture, based on kelps and other algae has been brought into consideration. No competing uses exist for these areas which are located in the continental shelf regions, and the harvesting costs are reasonable. After extraction of commercially important components, such as alginic acid or carrageenan, the remaining biomass could be used for the production of methane by anaerobic fermentation.

Of more immediate interest from the point of view of energy generation are the currently available organic waste products. The potential of obtaining energy from these wastes has been the subject of lively discussion, particularly by Reed (*6*). The estimated amounts are shown in Table 2. It should be stressed that the magnitudes given in this table represent coarse estimates only. Some of the values refer to total amounts produced; others to amounts considered to be collectible in practice. The latter is the case for logging residues. The actual amount of biomass consisting of branches, foliage, and stumps must be much larger than 50 million metric tons—perhaps as much as 180 million metric tons.

The total amount of available residues may be 1 billion tons (*7*), equivalent in fuel value to approximately 15 percent of the total energy needs in the United States. Prime consideration should be given to residues that are already collected, such as urban waste, manufacturing residues from wood, and cattle manure. Currently, these residues require disposal, an operation that usually costs approximately $5 per dry ton. The elimination of the disposal cost represents an economic advantage for the energy generation from these fuels. It is consequently understandable that the energy potential of urban waste has generated a great deal of interest and research (*8*). The logging residues are usually disposed of by burning (slash burning), while the agricultural residues are plowed under in the fields. Both of these disposal operations add to the fertilizer pool of the land. The realization of energy generation from these residues would require collection and transportation, a costly operation, especially in the case of logging residues (> $20 per dry ton). Grantham (*2*) has consequently suggested that the collection of forest residues for energy can only be economically justified if sufficient amounts of high-value raw material for the forest products industry can be salvaged from this waste. As far as agricultural residues are concerned, collection and transportation costs have not been estimated, but are likely to be a great deal less than in the case of forest residues. In view of the large mass of these wastes, more than 350 million metric tons annually, the energy potential of agricultural residues would look particularly attractive except for the problems caused by seasonal availability. It is not known how feasible and how costly it would be to store these residues. Under any circumstances, it appears that the use of agricultural residues should be integrated with that of continuously available fuels.

Table 1. Comparison between renewable resources and fossil fuels in the production of energy and chemicals.

Production	Amounts used or produced (million metric tons)	
	Wood	Fossil fuels
Consumption for energy (*2*)	63	1800
Synthetic polymers and chemicals	2	18
Lumber and plywood production	~175	
Paper products	60	

Table 2. Estimated annual volumes of urban, agricultural, and wood waste.

Waste	Million metric dry tons per year
Urban (*6*)	
Municipal waste	160
Sewage	60
Agricultural (*7*)	
Cereal straws	132
Other plant residues	220
Cow manure	210
Wood (*2*)	
Logging residues	50
Manufacturing residues	15
Total	847

Forms of Energy Generation from Renewable Resources

After the suggestion by Reed (*6*), renewable materials can be divided into dry biomass, with moisture content of 50 percent or less, and wet biomass, in which the difficulty of removing excess water makes its use as solid fuel impracticable. Sewage and cattle manure belong to the latter category.

The options for generating energy from dry biomass are outlined schematically in Fig. 1. Conversion of waste materials to solid fuels is generally possible by relatively simple means; the intrinsic calorific value is recovered in combustion, reduced only by the amount required for the evaporation of water, ash is utilizable as fertilizer, and the gaseous emissions are essentially free of sulfur dioxide and other pollutants such as mercury. On the other hand, this form of energy generation requires costly boiler installations, and particulate emissions are sometimes a problem. Conversion of biowastes to gaseous or liquid fuels improves their versatility, storage, and transportation, but there is a net loss of intrinsic energy value associated with the conversion. This energy loss is particularly high in the conversion of wood waste to fuel oil (*9*), resulting in the retainment of only one-third of the original calorific value in the product.

Should renewable resources be converted to liquid fuels, such as fuel oil or methanol? The decision of the city of Seattle, Washington, to build a methanol plant based on municipal waste (*8*) has often been cited as a pioneering example in this direction. What is not realized is that the decision was based on two circumstances of strictly local nature: (i) lack of market

for solid fuel and (ii) lack of market for low Btu gas. Thus, it can be concluded that, while the production of methanol from municipal waste appears to be economical, direct combustion or gasification are more attractive alternatives for the moment. The massive need for synthetic natural gaseous (SNG) and liquid fuels will probably be satisfied from coal in the future (*10*).

Combustion of wood and other renewable resources for energy can probably be improved a great deal by the application of modern engineering principles. To an even greater degree, the same thing holds true for the large-scale production of low Btu gas from wood and other renewable resources (*11*), which is still in its infancy. Initial results look promising. The heating values of wood gas are similar to those of coal producer gas—150 to 200 Btu per cubic foot (1 foot = 0.3 meter) with air and 270 to 330 Btu per cubic foot with oxygen. Wood gasification requires no steam and less oxygen than coal gasification. The gas is practically free of sulfur and has a higher ratio of H_2 to CO than that of coal gas (*7*). On the other hand, the efficiency of gasification of wood is some 7 percent less than that for coal when expressed as heating value of gas divided by that of the fuel used.

After removal of excess moisture, solids, and condensibles, low Btu gas, whatever the source, consists of hydrogen, carbon monoxide, carbon dioxide, and some methane and other hydrocarbons. Combustion of this gas may often be an advantageous alternative to incineration of the original fuel, which requires large-scale scrubbers to remove particulates from the stack gas. It can also be applied to the energetically favorable gas turbine steam plant combination. Gasification deserves to be evaluated as a means of gleaning energy from wood and bark waste at pulp mills and forest products manufacturing plants.

Pyrolysis gas from renewable materials would appropriate feedstock for the production of SNG (largely methane), except for the fact that the differences of the sources preclude the production of sufficiently large quantities in one location. An alternative and more promising method of producing methane from renewable resources is bioconversion by means of anaerobic fermentation. Despite the customary recovery of methane from municipal sewage plants in Europe, detailed engineering evaluations about the feasibility of this type of energy generation from different types of waste are not available. An alternative to methane generation from wet waste products is liquid combustion (Zimmerman process) (*12*). The clarification of the relative merits of the two approaches in future engineering studies is of outstanding importance.

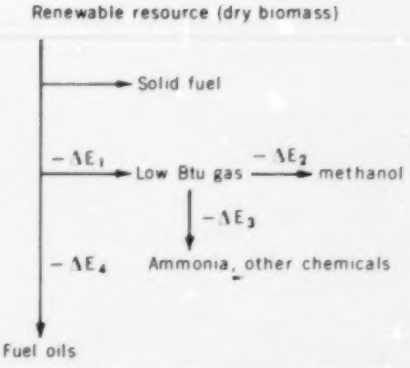

Fig. 1. Options for generating energy from "dry" renewable sources. ΔE signifies energy consumed in conversion.

Renewable Polymer Potential of Resources

The ready availability and low price of petrochemical feedstocks provided a tremendous competitive edge for chemicals and synthetic materials manufactured from these sources during the period after World War II. The price differential was large enough to virtually stagnate the development of new chemicals from wood and coal and to eliminate the wood distillation industry and the manufacture of many organic solvents by fermentation of carbohydrates. The question arises as to what degree the continuously decreasing availability and higher prices of petroleum and natural gas feedstocks will reverse the previous trend and increase the use of renewable resources as feedstocks for chemicals and polymers.

It is obvious that the reversal is most likely to occur in areas where a renewable product with low demands for energy in its manufacturing has remained competitive until now with petrochemical synthetics (*13*). An example of this is cotton, which until now has held about 50 percent of the world textile market, compared to 29 percent supplied by synthetic fibers. Another example is natural rubber, which now satisfies 40 percent of the world market. It is to be expected that the current situation will also stimulate the development of improved production methods for cotton and natural rubber, thus further strengthening their competitive position.

The reversal is not as likely in cases where the conversion of renewable resource to product requires energy. This is the case with paper and board products competing with synthetic films in the packaging market. The paper industry in the United States now consumes an average of 27 million Btu's of purchased energy per ton of paper produced; the total amount corresponds to about 2 percent of the energy consumption in the United States. On the other hand, there are clear indications, especially if comparisons are made with the manufacturing practice in northern Europe (*4*), that it will be possible to reduce the amount of purchased energy to a fraction of its current amount by improved technology and better recovery of energy from the waste products.

The situation is not as favorable in the case of cellulose derivatives such as rayon and cellulose acetate that are used as plastics, films, and textiles (*7*). The current production volume of these materials is 2 million metric tons per annum in the United States. The manufacture of these products consists of two processes: (i) conversion of wood to chemical cellulose (dissolving pulp) and (ii) conversion of chemical cellulose to derivatives. The former process produces low yields (28 to 33 percent of wood) and consumes significant amounts of energy (0.3 to 0.6 pound of oil per pound of cellulose). The second conversion requires capital-intensive mills, which are currently experiencing severe pollution problems. The question arises of whether or not better methods of manufacturing cellulose derivatives could be evolved from intensified research and development work. There ought to be more direct ways of converting wood and other lignocellulosic materials to cellulose derivatives than the traditional processes.

Starch is a relative newcomer in the polymeric materials field, and its annual consumption in this area amounts only to 25 thousand tons. Since it is isolatable from corn in 60 percent yield by a simple process, its use in chemical industry has the potential of rapid expansion, possibly to the level of 1 million metric tons annually. It can be used for the production of polyurethane-type plastics and foams, polyelectrolytes, and the like.

Chemical and By-product Potential of Renewable Resources

In the chemical pulping of wood, 42 to 52 percent is usually recovered as the fibrous product, incorporating the cellulose component, a part of the original hemicelluloses, and some residual lignin. Thus, more than half of the original organic material is not recovered as a product, but rather is used as fuel to provide process energy. These materials, obtained in an

amount of over 20 million metric tons annually, could be feedstocks for the production of chemicals but remain in a noncompetitive position during the period of cheap petrochemicals. Notable exceptions are tall oil, a mixture of fat and resin acids, and turpentine, a mixture of monoterpenes. Both are extractive products isolated from kraft pulping. Together with similar products isolated from pine trees and stumps (oleoresin and gum turpentine), the annual production volume amounts to 0.5 million metric tons. In addition, lignin products in the form of lignin sulfonates have found gradually increasing applications as dispersants, particularly as oil well drilling additives, as emulsifiers, and as complexing agents (*14*).

The competitive position of by-products from pulping has substantially improved and will continue to do so. New potential products include those derived from hemicelluloses and from lignin.

In the conventional acid sulfite pulping process, the majority of hemicelluloses are hydrolyzed monosaccharides. Conversion of these sugars by microorganisms such as *Candida utilis* to proteins edible for both humans and animals has been known for a long time but practiced on a very limited scale. Similarly, the fermentation of hexose sugars to ethyl alcohol in sulfite waste liquors has been quite limited. However, expansion of protein and ethanol production from sulfite waste liquors is limited because less than 10 percent of the chemical pulp produced in the United States is manufactured by the sulfite process and the production is currently declining.

There are many alternative sources for monosaccharides. In the widely used kraft pulping process, they are converted to saccharinic acids but could be partially recovered by steam hydrolysis of wood prior to pulping. They can be obtained by acid-catalyzed hydrolysis of practically all vegetative biomaterials, including wood and agricultural residues, and by enzymatic hydrolysis of those with low lignin content. These include grain, starch, waste paper, and algal biomass. While monosaccharides undoubtedly could be produced on a massive scale, it is not yet clear what sources would be the most advantageous ones.

Both hexose and pentose sugars are appropriate feedstocks for the production of protein. Pentose sugars are readily converted to furfural, a raw material for a number of resins and adhesives and a potential intermediate in the manufacture of nylon. Agricultural residues and hardwoods, both rich in xylans, are appropriate starting materials. Limited quantities of furfural are now produced from corncobs, and the integration of furfural production with kraft pulping of hardwoods has been demonstrated.

Fermentation techniques for making use of hexose sugars show promise as low-energy production methods. In addition to production of ethanol by fermentation, similar methods are known to produce acetic, butyric, and lactic acids as well as glycerol. Many other products are undoubtedly possible, as is bioconversion to specific polysaccharides. A virtually unexplored area is the conversion of hexoses to anhydro sugars such as levoglucosan (glucose 1,6-anhydride), which could serve as intermediates for many products (*15*). Anhydro sugars may also be obtained from plant materials by controlled pyrolysis. Levulinic acid, $CH_3COCH_2CH_2COOH$, a product obtainable by high-temperature hydrolysis of hexoses or plant materials in general (*16*), deserves reevaluation as a chemical intermediate. The carbohydrate acids that are formed in massive quantities (approximately 14 million metric tons per annum) in the kraft pulping process should also be studied in terms of intermediate potential.

There are very realistic possibilities of expanding the current use of lignin products to such areas as synthetic polymers or the production of low-molecular-weight phenols (*17*). It is known that kraft lignin can be applied as an additive (up to 20 percent) to phenolic resins, but it cannot be used as a replacement for phenol in these polymers. It can also be used as a component in polyurethanes. Suitable chemical modifications may improve its properties in these applications. Kraft lignin is a potential substitute for carbon black in automobile tires (*14*).

The hydrogenolysis of kraft and other lignins has been shown to yield low-molecular-weight phenols in yields up to 55 to 65 percent (*17*). This process has now become economically feasible. Extensive studies are needed to compare the response of different types of lignin toward hydrogenolysis, for example, those of softwood, hardwood, and grass lignins.

The question may be asked whether chemical feedstocks from renewable resources should be recovered as by-products of the pulping industry or whether separate chemical plants should be set up to produce, in an integrated manner, a number of chemicals from renewable resources. Since large amounts of lignin and hemicellulose materials are already available in large quantities from pulping processes, the former alternative would seem to possess more immediate feasibility. "Integrated chemical plants" based on renewable resources should nevertheless be contemplated; one such proposition was made in a recent article by Goldstein (*18*). According to his proposal, polysaccharides in wood would be converted to ethylene by complete hydrolysis to sugars, fermentation to ethanol, and dehydration, while the remaining lignin would be converted to phenol and other aromatics by hydrogenolysis. Ethylene and aromatics could be used as feedstocks for the manufacture of conventional synthetic polymers. However, fermentation ethanol (from grain) is currently not competitive with that produced by the hydration of ethylene as an industrial solvent. It has been estimated that competitiveness will be reached when crude oil prices have reached $20 per barrel (*13*). On this basis, it seems probable that the production of ethylene by dehydration of ethanol will become economically feasible after approximate doubling of current crude oil prices.

Production of Chemicals by Gasification

It was emphasized above that pyrolysis gasification of organic waste products could be used advantageously in the production of energy. The same gas can also serve as synthesis gas to produce such chemicals as methanol, ammonia, methane, and other hydrocarbons by well-known technology. The gas produced from lignocellulosic materials has the advantages of a higher ratio of H_2 to CO and lower desulfurization costs in comparison with coal gas. Prahacs *et al.* (*19*) has evaluated the processes of converting wood waste to methanol or ammonia and arrived at favorable conclusions concerning the feasibility of such processes. There are only a few locations, however, where sufficient amounts of renewable materials can be supplied on a continuing basis. Industrial plants producing methanol or ammonia from renewable resources would be limited in size to small production units. It would seem more logical, therefore, to investigate the feasibility of large plants that could be operated with both fossil fuels (oil and coal) and wood or agricultural waste. For example, ammonia fertilizer plants in agricultural regions could rely on the plentifully available agricultural residues during harvesting seasons and shift to the use of fossil fuels when these residues are not available.

Conclusions

Of the renewable resources available in the United States, organic waste products with an approximate volume of 1 billion tons annually represent significant poten-

tial in conservation of fossil fuels. The largest impact could be accomplished in the generation of energy, while less significant savings of fossil fuels are possible in using renewable resources as feedstocks for chemicals. In view of the limited and diffuse availability of renewable resources, they should generally be regarded as auxiliary fuels and chemical feedstocks rather than as direct substitutes for fossil fuels.

The clarification of the exact potential of renewable resources requires a substantial research effort. The area should be looked at as a whole, rather than having separate groups of parochial researchers concentrate on forest residues, waste products from the pulping industry, agricultural residues, or marine resources. This calls for a broader interdisciplinary endeavor than is possible in the framework of existing government agencies. The prime targets for research ought to be the relative economic feasibility of collection and storage of residues, improved technology of direct combustion, of gasification, and of bioconversion to methane, as well as hydrolytic and pyrolytic conversions to chemical feedstocks. Specific information is needed concerning lesser known materials such as cow manure or algal biomass.

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